DEVELOPMENT OF BONDING METHODS AND ENERGY ABSORPTION OF SANDWICH PANELS FOR THERMOPLASTIC ADVANCED COMPOSITES

by

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ABSTRACT

Given their high strength-to-weight and stiffness-to-weight ratios, sandwich composites continue to be considered for automotive applications. Thermoplastic materials, while difficult to bond, have an increased ease of manufacture and may be reprocessed, making them an attractive alternate to thermoset composites. This investigation focused on the evaluation of adhesives and surface treatments for both nylon and polypropylene thermoplastic composite adherends made from Towflex® pre-impregnated composite fabric. A manufacturing method was established for thermoplastic plates, which produced an acceptable surface finish without contaminating the bonding surface. Adhesives and surface treatments were evaluated using lap shear (ASTM D 3163) and cleavage (ASTM D 3433) test methods. The most promising adhesive/surface treatment combinations were selected for bonding of sandwich composites with two different core materials: balsa wood and polyurethane foam. Initial sandwich configuration testing consisted of flatwise tensile (ASTM C 297) and core shear (ASTM C 273) test methods. These tests provided insights into the sandwich properties and revealed any incompatibilities between the adhesive and the core. Follow on sandwich configuration evaluation consisted of edgewise compression testing, both statically (ASTM C 364) and dynamically. These tests determined the strength and ability of these sandwiches to absorb energy under two different types of loading.

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1 INTRODUCTION

The use of advanced composites materials in automobiles is on the rise. For example, the Chevrolet Corvette has been focusing on using lighter materials to increase vehicle performance with the use of sheet molding compound (SMC) reinforced with random chopped fiberglass. Although this is still the primary use on the Corvette, monolithic and sandwich composites utilizing continuous fibers are increasingly being incorporated. The benefit of incorporating these structural materials is to reduce weight thereby improving efficiency and performance. Such applications have focused primarily on thermoset composites. However, thermoplastic composites offer reduced cycle-times, improved ease-of-manufacturing and are recyclable. The greatest difficulty, however, is bonding them to other structures. Previous research at the University of Utah, focused on characterizing candidate sandwich composites for use in automotive floor applications, indicated that thermoplastic composite facesheets were difficult to bond to core materials [1]. Based on this previous research, this current study focused on developing and evaluating joining methods between thermoplastic composite facesheets and candidate core materials in sandwich composites.

Sandwich composites are comprised of a core material that is sandwiched between two laminated facesheets. The core material is much thicker than the facesheets, is generally low density and is intended to carry shear stresses from transverse loading. The facesheets are thin, resin/fiber reinforced sheets with high specific stiffness and strength

to resist tensile and compressive loadings in bending. Overall, sandwich structures offer increased strength-to-weight and stiffness-to-weight ratios.

When bonding thermoplastics, the removal of surface contamination due to low molecular weight molecules can improve bonding and is commonly achieved by mechanical abrasion and solvent cleaning. Mechanical abrasion includes sanding, grinding, and grit blasting all of which mechanically alter the surface to increase wet-out and surface energy. Solvent cleaning relies on the fact that low molecular weight molecules go into solution more readily than the larger molecules. Since there are no known low-temperature solvents to remove contaminants from nylon or polypropylene, solvent cleaning is not a viable option for removing contamination as it is with thermoset epoxies. However, using an acidic solution for surface etching can improve adhesion of thermoplastics.

Increasing the surface energy of unmelted thermoplastics to improve wetting and increase bond strength can be achieved by a number of methods. Even though it requires handling of hazardous materials, oxidation by strong chemicals can improve bondability. The use of flame, sulfonation and plasma treatments not only can clean the surface, but also can introduce polar chemical groups though oxidation. These procedures are currently practiced in industry and can result in good adhesion with common adhesives. A downside is that the benefits of these surface treatments are prone to fade over time or under elevated temperature, requiring them to be a process step just prior to bonding.

The thermoplastic facesheets used in this study featured both polypropylene and nylon matrices reinforced with continuous carbon fiber. The investigation has focused on improving upon the promising bonding methodologies for joining thermoplastic

substrates developed in a previous study at the University of Utah [2] and characterizing the bond performance. Additionally, these improved bonding methodologies were applied to the manufacture of thermoplastic sandwich composites. The core materials investigated were balsa wood, structural foam, and honey-combs. The thermoplastic sandwich composites were evaluated for their structural and energy absorption properties.

A consolidation method was developed yielding contaminant-free plates using a heated press with aluminum tooling surfaces and zinc stearate mold release for nylon reinforced carbon fiber and Kapton film for polypropylene reinforced carbon fiber. The manufacturing process was also adapted to improve surface finish and ensure plates were manufactured flat and free of warping. This process is comprehensively outlined and a summary of the removal of contaminants is given.

This investigation focused on improving the most promising adhesive, surface preparation methods, surface treatments, and procedures for polypropylene reinforced carbon fiber and applying the most promising adhesive, surface preparation methods, surface treatments, and procedures for nylon reinforced carbon fiber determined in a previous investigation at the University of Utah [2].

Multiple rounds of experimental evaluation were performed to investigate and characterize the bonding methodologies of the two different types of adherends, and the mechanical properties of the sandwich composites. First, a round of lap shear (ASTM D 3163) testing was used on the polypropylene reinforced carbon fiber to identify bond strength. Next, a round of fracture toughness testing (ASTM D 3433) on polypropylene and nylon reinforced carbon fiber to investigate fracture toughness.

The two most promising candidates from each thermoplastic group identified in lap shear and fracture toughness testing were selected for follow-on testing under different environmental conditions.

The two most promising candidates from each thermoplastic group identified in lap shear and fracture toughness testing were selected for follow-on testing to evaluate their strength using glass fiber reinforced composites.

Eight of the most promising candidates were selected for sandwich panel manufacture and testing: four from nylon thermoplastic composite facesheets and four from polypropylene thermoplastic composite facesheets. Flatwise tension (ASTM C 297) and core shear (ASTM C 273) were used to determine the strength of the core/adherend interface, as well as the strength of the overall sandwich composite. These tests were also an excellent way to determine any adhesive/core issues.

After identifying any adhesive/core issues, a down-selection of the initial sandwich panel candidates occurred where both nylon and polypropylene were selected for energy absorption testing. Static edgewise compression testing (ASTM C 364) and a dynamic edgewise compression test [3] were used to determine the ultimate strength of the thermoplastic sandwiches as well as the energy absorbed.

2 LITERATURE REVIEW

The use of composite materials in the automotive industry continues to grow, although affordability, energy absorption, surface finish quality, and recyclability are difficult issues. Although a majority of the focus to date has been on monolithic composite laminates, composite sandwich structures are being considered for selected automotive applications to provide even greater strength-to-weight and stiffness-to-weight ratios. Composite sandwich structures consist of an inner, low-density core encased by and bonded to a pair of thin, outer composite facesheets. Currently, the primary interest for these sandwich composites appears to be in roof and floor applications, where the improved bending properties of sandwich structures are a major consideration [4].

Unlike thermosetting materials, thermoplastic materials can be repeatedly heated and melted at elevated temperatures. Combining this characteristic with the decreased cycle time compared to thermosets, thermoplastics become quite attractive for manufacture. However, the end use must be considered, because as the glass transition temperature of the thermoplastic is approached, the Young's modulus decreases [5]. Thus, the use of thermoplastics in higher temperature environments such as in engines could cause softening and loss of structural integrity. Details on the specific thermoplastics used in this investigation are provided later in this report.

Thermoplastics are typically insoluble in each other so that the adhesive and the adherent must be the same polymer for melt bonding. Since they do not mix chemically,

polyethylene will not adhere to polypropylene when melted together. Welding of adherends of like material has become an accepted method of joining; however this can be difficult with complex shaped parts [6]. Adhesives tend to have difficult wetting out or spreading on thermoplastics because of a low surface energy and thus require elevated temperatures to develop strong bonds. Due to a smooth, impermeable surface and low molecular weight molecules interfering with the bond, mechanical interlocking directly onto the surface can be difficult [7].

Often the surface is contaminated due to low molecular weight molecules migrating to the surface during consolidation. Removal can improve bonding and is commonly achieved with mechanical abrasion or solvent cleaning. Mechanical abrasion includes sanding, grinding, grit blasting or any other process mechanically changing the surface. Mechanical abrasion (sanding or grit blasting) of the thermoplastic surface was found to improve bond strength in the previous University of Utah research [1]. Solvent cleaning relies on the fact that low molecular weight molecules go into solution more readily than the larger molecules. While solvent cleaning has been shown to be successful in removing such material from thermoset epoxies, it is much more difficult for polypropylene and nylon thermoplastics, since there are few if any reasonable low-temperature solvents for these materials [7, 8].

Increasing the surface energy of unmelted thermoplastics to improve wetting and increase bond strength can be achieved by a number of methods. Even though it requires handling of hazardous materials, chemical oxidation can greatly improve bondability. The use of flame, sulfonation and plasma treatments not only cleans the surface, but also introduces polar chemical groups though oxidation. These procedures are practiced in

industry and can be successful when combined with the proper adhesive materials. These surface treatments do tend to fade under elevated temperature conditions or over time and thus such processing should be done shortly prior to bonding [7, 8].

Primers are often used to enhance the bonding of an adhesive to a substrate. In some cases where the adhesive will not bond strongly directly to a substrate, a substance may be used as an "intermediary" between the adherend and the adhesive. If a very thin layer of this substance is applied to the substrate, it may form a primer to which the adhesive will develop a strong bond [7, 8].

The aerospace industry has provided much of the research of joining thermoplastic composites to date because joining is critical to the manufacture of aerospace structures. Much of this research took place in the late 1980s and early 1990s in an attempt to move the use of thermoplastics into mainstream aerospace use. The joining methods commonly tested can be grouped into two categories: standard thermoset joining methods adapted for thermoplastics and methods specific for thermoplastics. The standard thermoset joining methods are co-consolidation, adhesives and fasteners. However, co-consolidation of thermoplastics is actually a melt fusion process as opposed to co-curing for thermosets. Joining methods specific for thermoplastics include resistance welding, induction bonding, ultrasonic welding and microwave bonding [9].

Previous research performed at the University of Utah focused on the characterization of candidate sandwich composites for the use of automotive floor applications [1]. Six sandwich configurations utilizing thermoplastic materials—carbon/nylon, carbon/polypropylene and glass/polypropylene with polyurethane and balsa wood cores—were tested. Candidate adhesives were identified and flatwise tensile

testing was used to identify the best-suited adhesives to bond the facesheets to the core: Lord 320/322 toughened epoxy and Loctite 907 epoxy. Preliminary results also showed that surface preparation of the composite—specifically abrasion—increased the bond strength.

Further flatwise tensile and core shear testing identified that these thermoplastic sandwiches predominantly failed between the adhesive and the facesheet as shown in Figure 2-1. As noted in these previous studies, the bond strength between the facesheet and the adhesive was lower than the strength of the core itself which is undesirable (Figure 2-2). Based on the poor bond strength of the parameter groups used, only thermoset facesheets were used for future sandwich composite evaluation. However, this previous testing [1] identified the need for further research to develop and evaluate joining methods between thermoplastic composite facesheets and candidate core materials as is undertaken in this study.

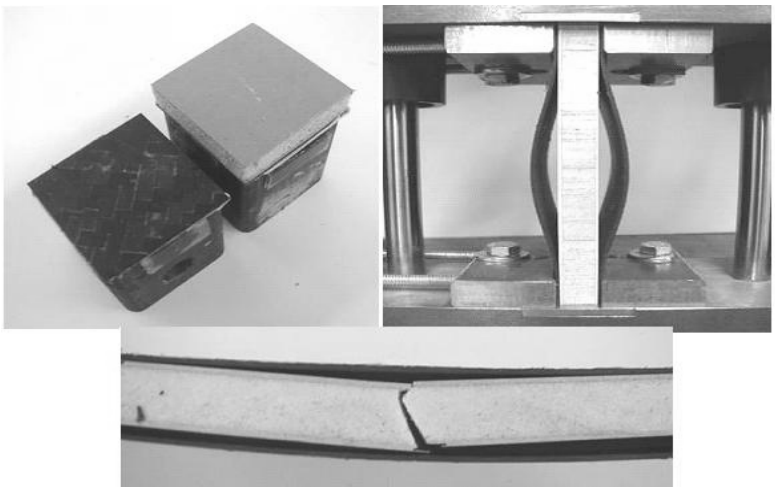

Figure 2-1: Previous testing at the University of Utah involving bonding of thermoplastic composites resulted in adhesive or interface failure [1].

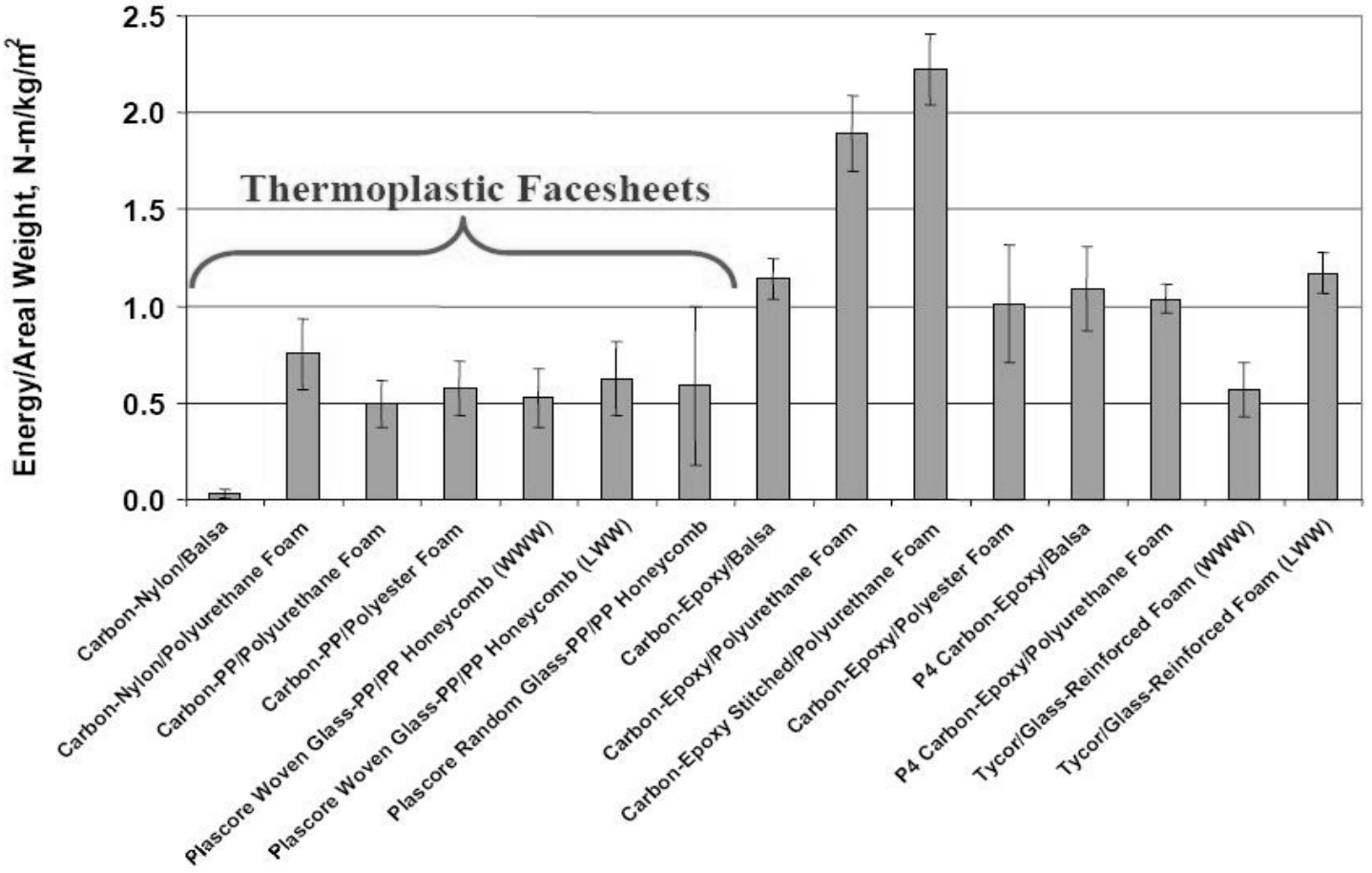

Figure 2-2: Three-point flexure testing results from previous University of Utah research [1] with lower bond strength thermoplastic composite facesheets indicated.

In a study focusing on newly developed adhesives in the late 1980s, Powers and Trzaskos [10] investigated fastening techniques for the use of advanced thermoplastic composites for structural applications. Lap shear testing was performed with two structural epoxy film adhesives and two structural curing epoxy adhesives. Grit blasting, as well as grit blasting followed by a solvent wipe and plasma treatments, were used as surface treatments. The authors concluded that each of these treatments was effective with these adhesives and sufficient strengths were achieved in all cases. It is also interesting to note that a correlation was performed between the strength of the bonded joint and the number of plies and ply orientation used. Shear strength was shown to increase as laminate thickness increased to a nominal thickness of 0.25 cm (0.10 in). In addition, laminates with surface plies having fibers oriented parallel to the shear load had at least 15% improved shear strength.

Prior to the above studies, Kodokian and Kinloch [11, 12] determined that the use of light abrasion/solvent wipe treatment with structural epoxy adhesives was inadequate. The resulting joints were relatively weak and the data had significant scatter. Adhesive or interfacial failure was observed. They determined a more comprehensive study was needed, which led to these later studies of more specific areas. Two composite materials were used—carbon fiber reinforced PEEK thermoplastic and epoxy thermoset. Two toughened epoxies and PEEK hot-melt were used in conjunction with simple abrasion, molding next to clean aluminum foil followed by an acid wash, acid etch and corona discharge. A double cantilever beam test was used with a crack initiated at one end.

All four treatments were successful with the use of the epoxies in bonding the thermosets, but the simple abrasion was not successful. In addition, the use of the

aluminum foil and acid etch did not increase bond strength significantly, indicating that surface contamination from mold release is not the essence of the problem. This finding was confirmed with the use of XPS to determine that silicone and fluorine levels were very low. Parker [13] similarly determined that initial bond strength is related to the presence of contaminants on the adherend surface. Thus, confirmation of a clean surface after adherend manufacture is necessary.

Kodokain and Kinloch [11, 12] also found that the use of the hot-melt did increase bond strength with the PEEK samples, but had little adhesion with the thermoset adherends. Corona discharge did improve fracture energy (G_c) values and cohesive failures were noted with both materials.

Another factor that can influence bond strength is the bondline thickness. McKnight et al. [14] investigated the effects of adhesive cure cycle and final bondline thickness on bond strength. Using adherends of S-2 glass/polyphenylene sulfide, thermoplastic composites with a co-molded polysulfone surface layer were bonded using a high performance epoxy film adhesive and an epoxy paste adhesive. Results indicated that bondline thickness reaches an optimum level before resulting in decreasing strength values.

Silverman [15] chose a slightly different approach using six different joining concepts to achieve strengths approaching 93.0 MPa (13.5 ksi). The concepts included adhesive bonding using a commercially available epoxy system, mechanical fasteners plus adhesive bonding, resistance heating, focused infrared heating, ultrasonic welding, and a novel technique employing an amorphous thermoplastic film. Advanced thermoplastic composites specimens were made using PEEK reinforced with AS-4

graphite pre-preg tapes. Tensile lap shear coupons were used for screening the alternative joining methods and measuring the bond strengths. Surface preparation methods examined included grit blasting, acid etching, and cold gas plasma etch treatment. The fusion bonding methods of resistance heating, focused infrared heating, and ultrasonic welding used a thin film of the neat thermoplastic PEEK in the joint prior to fusion. Even though none of the methods achieved the intended strength, epoxy with plasma treatment had the highest joint strength at 41.6 MPa (6.04 ksi) with cohesive and adhesive failure occurring equally. The strengths of the other methods dropped significantly.

More recently, Loven [16] investigated the use of adhesives for structural bonding for the automotive and marine industry. Even though this study does not investigate scientifically beyond a case study, it does point out that thermoplastics and composites can be structurally bonded in application.

Little research has been performed to date using nylon thermoplastic composites. Wade et al. [17] did investigate the surface modification and adhesive bonding of a nylon 6,6 reinforced with unidirectional glass fiber. Wettability studies of plasma-treated specimens showed a significant reduction of contact angles in water, relative to untreated material. The most effective treatment used oxygen plasma. The increases in wettability observed were determined to be the result of two effects. First, the treatment resulted in an increase in the concentration of oxygen and nitrogen containing functional groups on the surface of the polymer. Second, the plasma treatment removed fluorine contamination, the source of which was identified as the PTFE mold release agent. The surface modification resulted in significantly improved adhesion between the composite

and an applied toughened epoxy adhesive. Thus, a considerable increase in the Mode II critical strain energy release rate, G_{IIc}, was observed following plasma treatment. Specimens treated in oxygen plasma showed the greatest improvement in G_{IIc} and resulted in a cohesive failure. Without plasma treatment, the specimens failed in an adhesive mode at very low values of G_{IIc}. Adhesion was further optimized by molding the nylon-6,6 plates directly against steel plates instead of PTFE thereby removing any chance of fluorine contamination.

As noted, previous significant research has focused on determining methods to successfully join thermoplastic composites. These investigations have largely used different surface treatment methods that include abrasion, acid etching and plasma treatment. However, other surface treatments exist such as flame, corona and sulfur exposure. Development of these treatments and advances in the others result in the need for further investigation and testing of a wider variety of surface treatments as is taken on in this study. Details of the surface treatments investigated and used are found below.

After suitable surface treatment and adhesive combinations have been found, they must then be applied to the making of sandwich panels. This investigation utilizes two ASTM standard tests, flatwise tension and core shear, and two modified tests, static and dynamic edgewise compression. These particular test methods were selected based on their ability to readily identify performance problems and to use in assessing performance for automotive applications.

Flatwise tensile testing (ASTM C 297) is used to evaluate the strength of the sandwich under loading in a direction perpendicular to the facesheets [18]. This test is often conducted first for sandwich composites to assess the as-manufactured performance

of the facesheets, the core material and the bond between the constituents. The primary functions of this test are to identify material compatibility problems associated with the facesheet, core, and adhesive as well as manufacturing related problems such as core crushing, improper facesheet consolidation, etc. The flatwise tensile strength and the failure location/failure mode are the most important information from these tests. A schematic of the test setup is illustrated in Figure 2-3. In order to produce flatwise stress in the sandwich construction, steel loading blocks are adhesively bonded to each facesheet. A cylindrical pin is seated in each loading block for a means of load application. The pins are used to distribute the applied load and reduce bending moments. Core shear testing (ASTM C 273) is used to evaluate shear properties of the core material [19]. Strength and stiffness properties are determined from shear deformation in planes parallel to the facesheets. This test does not produce pure shear. However specimen lengths are sufficient so that secondary stresses are minimal.

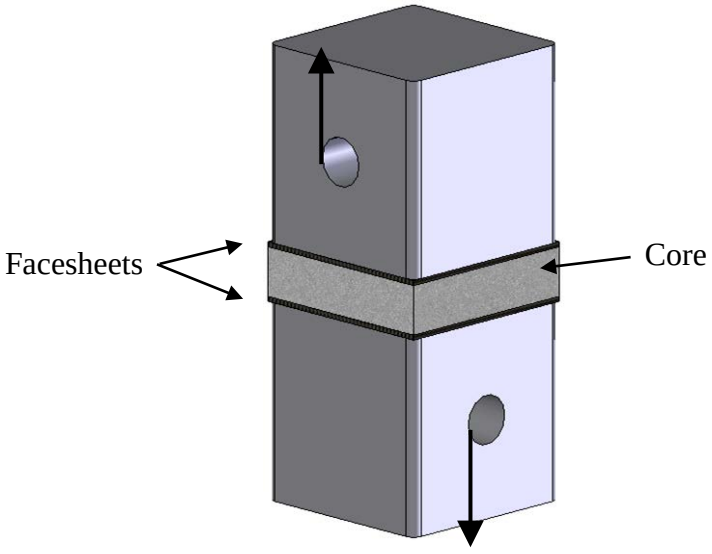

Figure 2-3: Flatwise tension test setup

The resulting properties from these tests are fundamental to the use and design of sandwich composites. From the load versus crosshead deflection curve, the following determinations can be made: the core shear stress at any point (including failure), the effective core shear modulus, and the energy absorbed in the core under shear deformation. Figure 2-4 illustrates the core shear testing setup. A metal plate is adhesively bonded to each facing of the sandwich construction. Load is applied at cylindrical pins seated in the metal plates such that the line of action passes through opposite corners in the core. Edgewise compression testing (ASTM C 364) is used to determine the compressive properties of a sandwich panel [20]. Additionally, the area under the load versus deflection curve can be calculated to determine the energy absorption of the sandwich under edgewise loading.

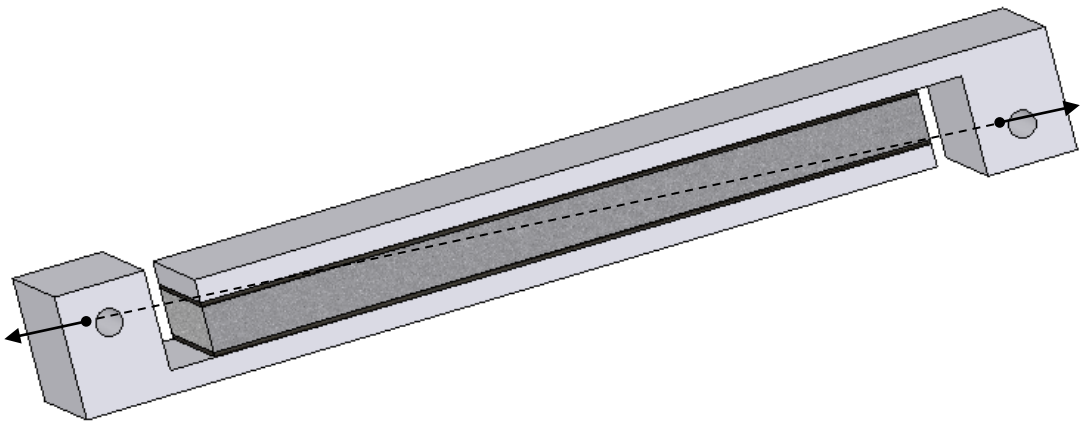

Figure 2-4: Core shear test setup

Previous work by Van Otten [21] investigated different edgewise crush initiators. These initiators encouraged the correct failure sequence of the sandwich to get the maximum possible energy absorption. It showed that there was a dependence between the stiffness of the facesheet and the strength of the core. If the facesheet was too stiff, and the core insufficiently strong, the facesheet would fail in buckling and separate from the core.

This finding led to the use of a modified static edgewise testing fixture, which had been used in a previous investigation at the University of Utah [3]. The fixure does not provide end clamping over 25.4 mm of the specimen at the top fixture instead it has two V-blocks as shown in Figure 2-5. These V-blocks realign the specimen during a buckling failure. This realignment allows the specimen to absorb more energy in the direction of compression.

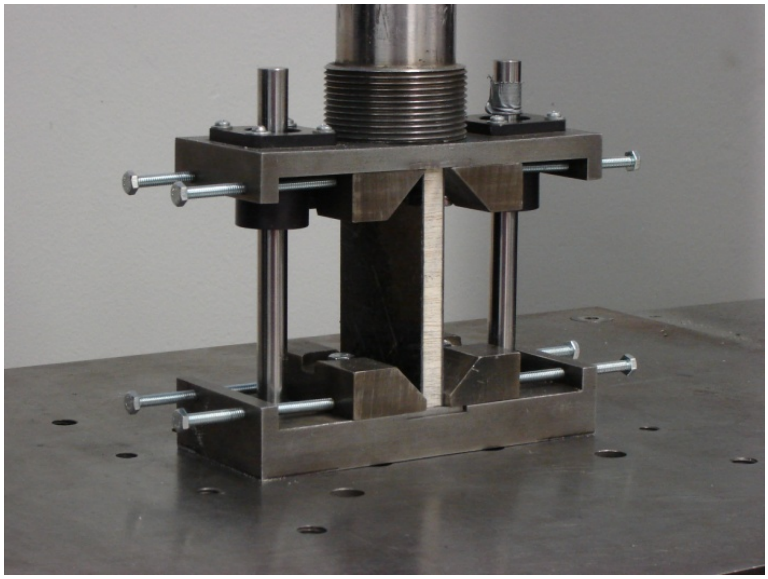

Figure 2-5: Modified edgewise compression fixture

There is currently no standard for dynamic edgewise compression testing. Thus, ASTM C 364 for edgewise compressive strength of sandwich constructions was used as a rough guideline for a previous investigation at the University of Utah [3]. The fixture used is the same geometry as that used in the modified static edgewise compression testing. However, the fixture is modified for use in a drop tower.

3 THERMOPLASTIC FACE SHEETS AND MANUFACTURING

3.1 Fiber Reinforced Thermoplastic Material

Two thermoplastic matrix materials reinforced with carbon fiber were used in all testing: polypropylene and nylon. The material, TowFlex® woven fabric reinforced thermoplastic, was produced by Hexcel Composites [22, 23]. TowFlex® laminates are manufactured using a compression molding process, where the material is heated to a specified melt temperature, pressure is applied for consolidation, and the resulting part is cooled while maintaining pressure. Details of this manufacturing process are outlined below.

The two thermoplastic materials used are very common and their use is widespread in the plastics industry. Use in the composites industry has been hindered by not only the ability to bond to other structures, but also the ability to adhere the thermoplastic matrix to the fiber reinforcement. Hexcel has successfully accomplished this bonding by spreading and powder coating continuous carbon and glass fibers with thermoplastic particles. The thermoplastic particles are subsequently melt-fused to the reinforcement fibers, producing a flexible material. Similar to a preimpregnated material, TowFlex® is then ready for consolidation off of the roll [22, 23].

3.1.1 Polypropylene

Polypropylene has a wide variety of uses from reusable storage to clothing. It is highly resistant to chemicals and has higher softening and melting temperatures than

other common plastics. The Young's (elastic) modulus is midrange, allowing for use where stiffness is needed, but has some resistance to brittle failure [5]. Polypropylene is an addition polymer, meaning it is synthesized from propylene. The propylene monomers are added together without the loss of any atoms or molecules to create the polypropylene chain as seen in Figure 3-1.

3.1.2 Nylon

Nylon is a family of synthetic polymers created by Dow Chemical in the 1930s. It was originally used in women's stockings, parachutes and more recently has been used in ropes, guitar strings and mechanical parts. Like polypropylene, the Young's modulus is favorable to provide stiffness without brittle failure. Unlike polypropylene the monomers used donate carbon to the polymer to create chains of six- sided carbon groups as seen in Figure 3-2. This process defines the two most common types of nylon: nylon 6 and nylon 6,6. Nylon 6,6 has an additional 6 carbon molecules repeated in the polymer chain that give extra strength and the resilience compared to nylon 6 [5]. The TowFlex® material in this study utilizes nylon 6.

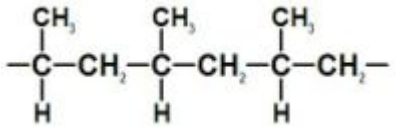

Figure 3-1: A general polypropylene chain.

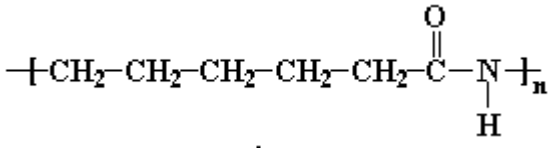

Figure 3-2: A general nylon 6 chain.

3.2 Manufacturing

The thermoplastic adherends used were fabricated at the University of Utah using a heated press to consolidate the TowFlex® woven fabric reinforced thermoplastic. Aluminum tooling surfaces were used to enhance surface finish. The consolidation cycle for the nylon-based TowFlex® was 1.0 MPa (~150 psi) at approximately 260ºC (500ºF) for approximately 15 minutes. The consolidation cycle used for the polypropylene-based TowFlex® was 1.0 MPa (~150 psi) at approximately 190ºC (375ºF) also for approximately 15 minutes. The tool was shuttled to a room temperature press and placed under 1.0 MPa (~150 psi) to increase the cooling rate.

Details of the manufacturing process for the thermoplastic plates are outlined below. Images, where useful, follow the specific process step. This detail includes modifications made for improved surface finished and consolidation while minimizing warping. Following the process is a summary of the contamination issues faced in using mold release and film barriers, justifying the contamination-free method that has been used.

3.2.1 Thermoplastic Plate Consolidation

Below is a detailed process instruction developed and used for the manufacture of the thermoplastic plates used in this investigation.

1. Put on sterile gloves to prevent contamination during all steps of the process (Figure 3-3).
2. Cutting Material
    a. Wipe table and tools with acetone and paper towel to prevent contamination.
    b. Using two squares and a straight edge for alignment, a 25.4 cm (10 in.) piece of Towflex® is cut off at the width of the roll (Figure 3-4).
    c. Noting the orientation, this piece is cut into 3 pieces 25.4 cm (10 in.) square, ensuring the selvage edge of the roll is not used (Figure 3-5).
    d. Extra material is stored for potential later use.

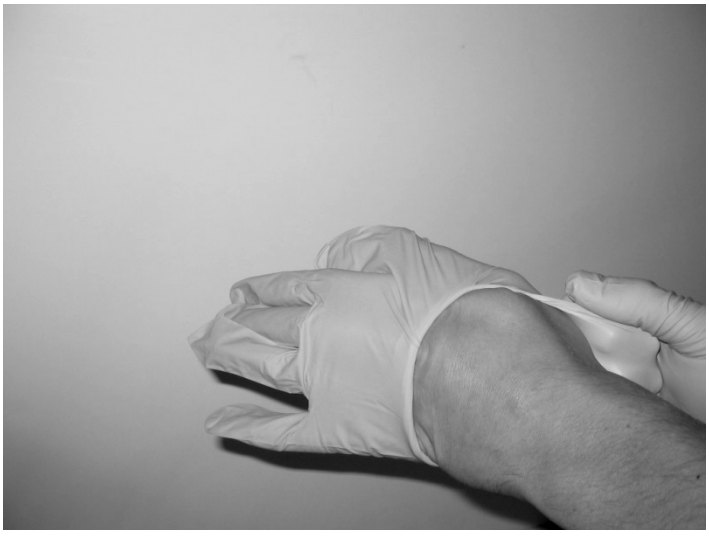

Figure 3-3: Sterile gloves are worn throughout the process to reduce contamination.

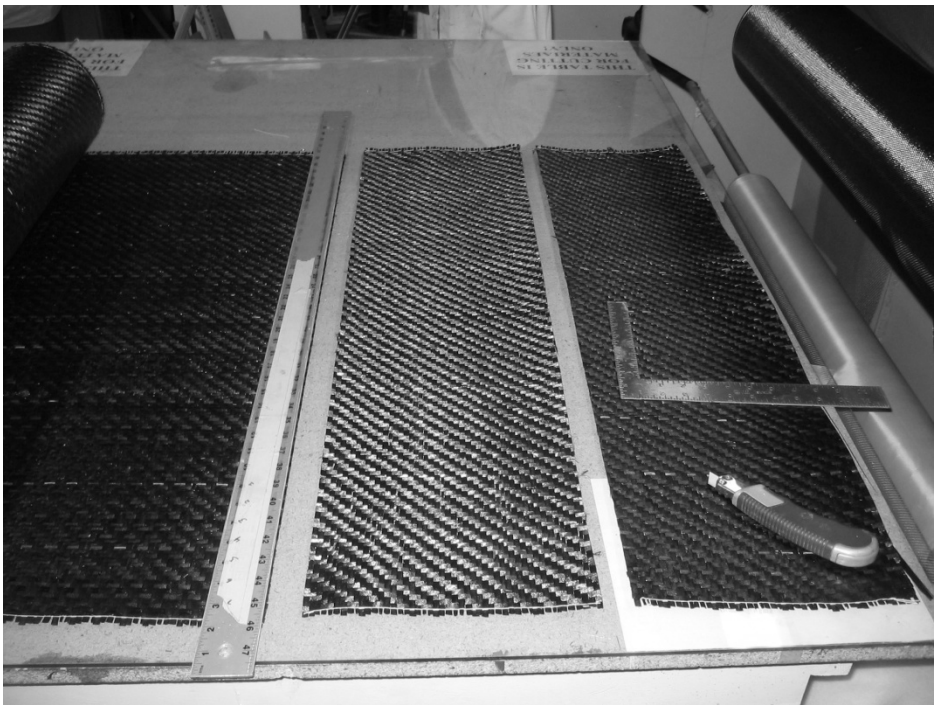

Figure 3-4: 10” strips of material are cut from the roll of thermoplastic material.

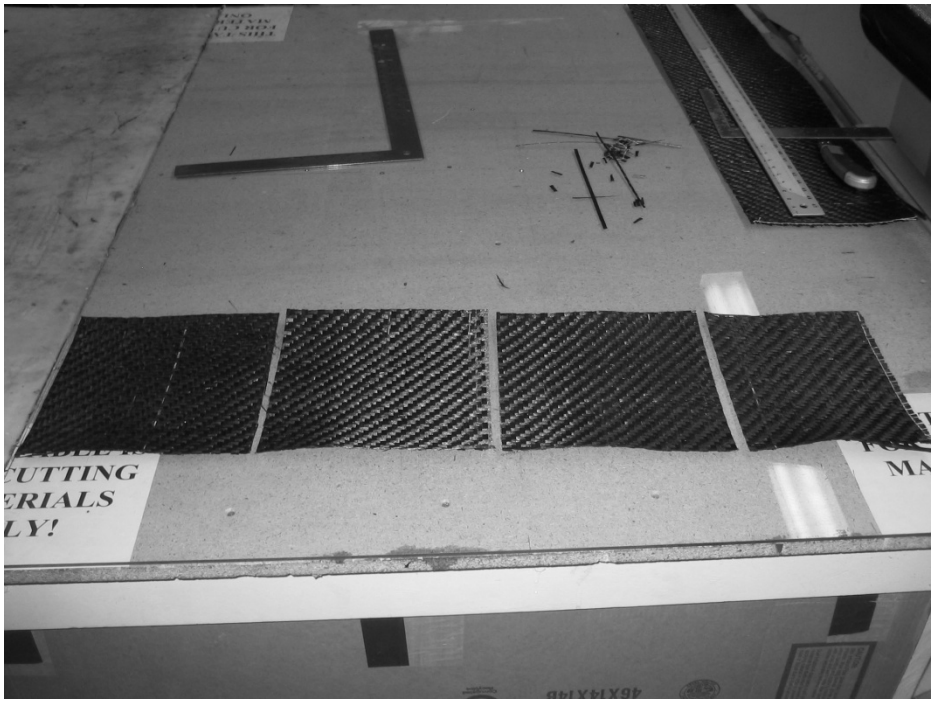

Figure 3-5: The 10” strips are then cut into pieces making 10” by 10” squares.

3. Tool Preparation - Nylon
    a. Aluminum plate 30 cm by 30 cm by 6.5 mm (12in x 12in x 1/4in) is used as a tooling surface.
    b. Aluminum foil is placed over the surface and folded around the edges. This provides a smooth repeatable surface with an adequate release so no initial or additional polishing is required with the aluminum sheet stock (Figure 3-6).
    c. Aluminum plate with foil is taken away from all thermoplastic materials and zinc stearate is applied with a side-to-side motion as a mold release. This is to prevent contamination from the spraying of the mold release in the laboratory.
    d. The released aluminum plate is brought back into the laboratory.
4. Tool Preparation – Polypropylene
    e. Aluminum plate 30 cm by 30 cm by 6.5 mm (12in x 12in x 1/4in) is used as a tooling surface.
5. Kapton film 30 cm by 30 cm (12in x 12in) is places on the lower aluminum plate (Figure 3-7).
6. Material Layup
    a. Lap Shear Specimens
        1. Four plies of the Towflex® material are used.
        2. Material is oriented in the 0/90 direction only.

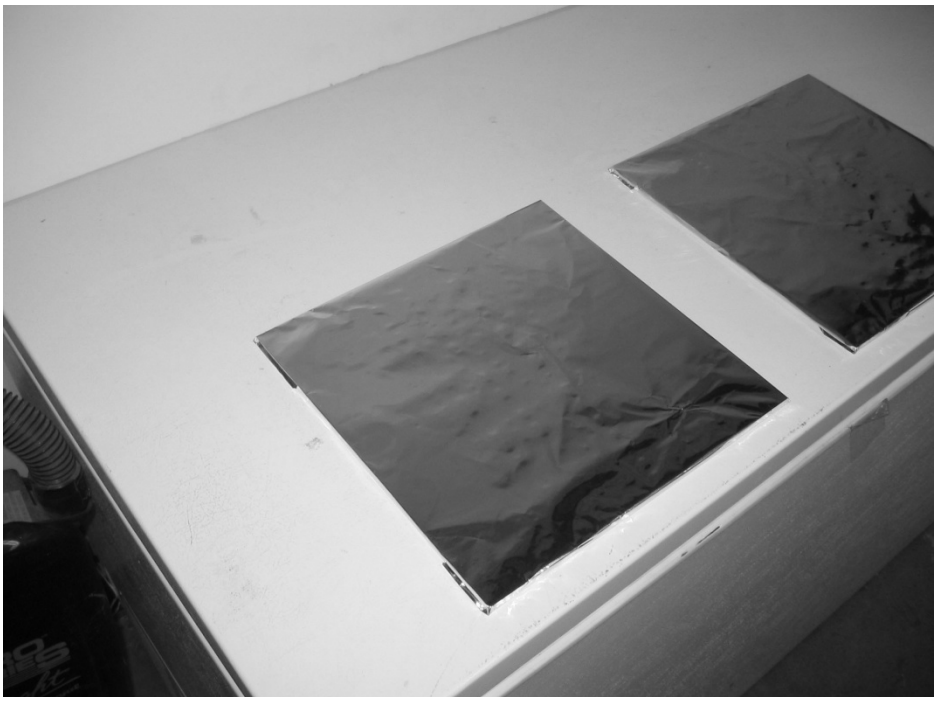

Figure 3-6: Aluminum foil is applied to the mold surface.

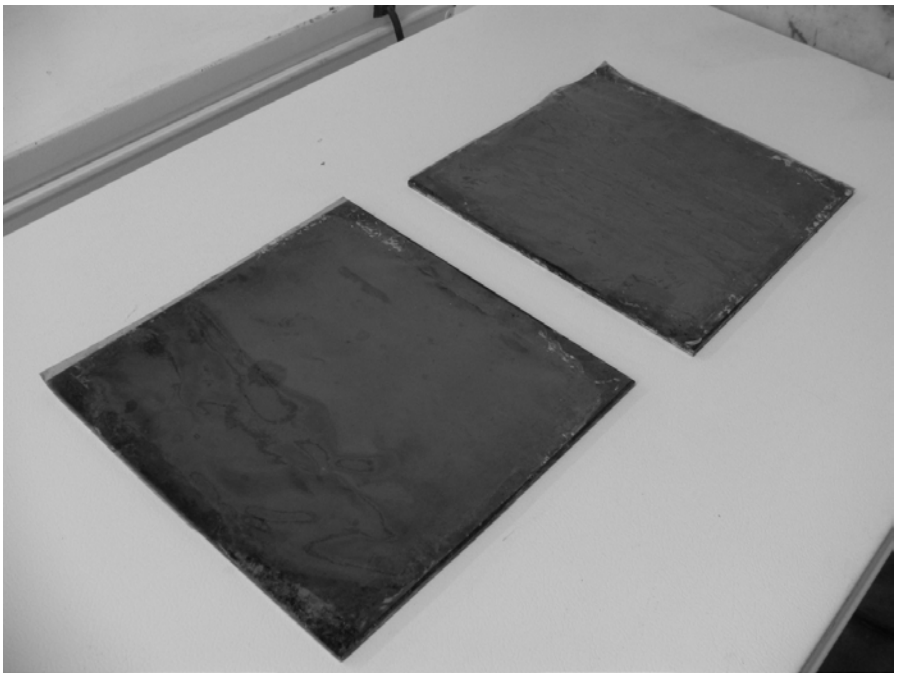

Figure 3-7: Kapton film placed on aluminum tool.

3. The curl of the material is placed onto the prepared tooling surface in the same direction so the edges curl up. This was found to give the smallest amount of warping of a finished plate (Figure 3-8).

b. G_{IC} Specimens

1. Eight plies of the Towflex® material are used.
2. Material is oriented in the 0/90 direction only.
3. The curl of the material is placed onto the prepared tooling surface in the same direction so the edges curl up. This was found to give the smallest amount of warping of a finished plate (Figure 3-8).

c. Flatwise Tension, Core Shear, Static Edgewise Compression, and Dynamic Edgewise Compression Specimens

1. Four plies of the Towflex® material are used.
2. Material is oriented at $[0/90,\pm45]_T$ for a quasi-isotropic layup.
3. The curl of the material is placed onto the prepared tooling surface in the same direction so the edges curl up. This was found to give the smallest amount of warping of a finished plate (Figure 3-8).

7. Shim Placement

a. Shim thickness is 1.5 mm (0.060 in).

b. Four shims are placed just inside the tool edge to ensure thermoplastic plate thickness.

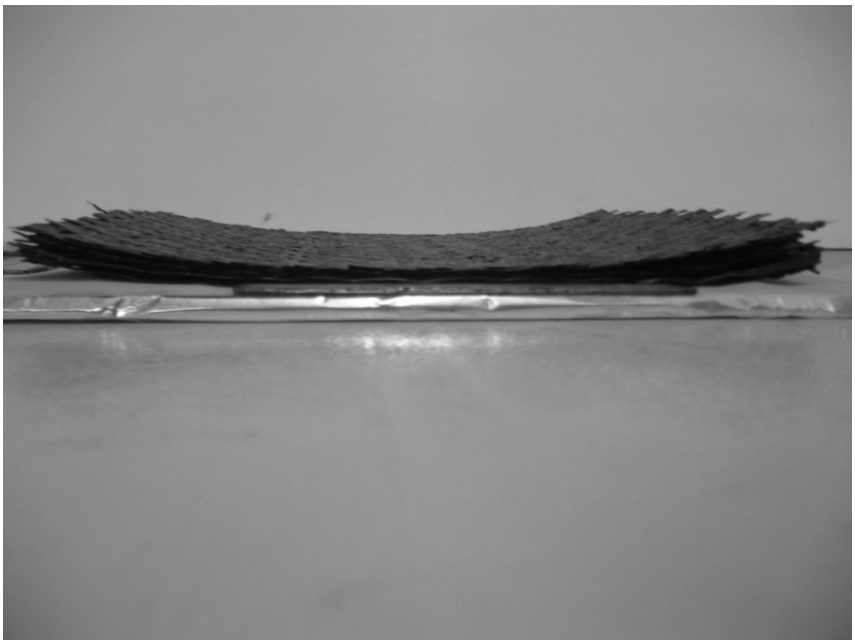

Figure 3-8: Material is placed onto the tooling surface.

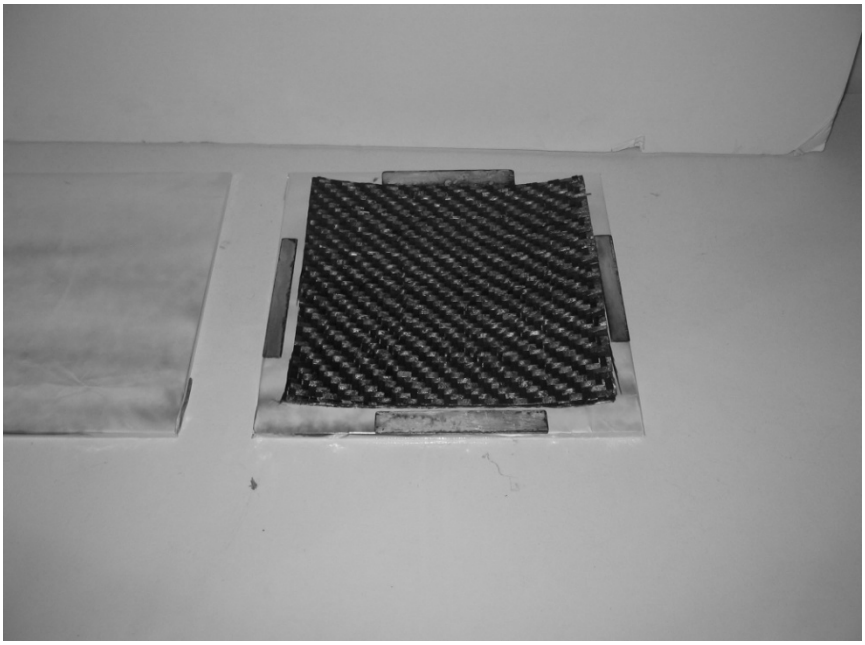

Figure 3-9: Shims are placed onto the tooling surface clear of interaction with thermoplastic material.

c. The shims must be placed in such a fashion so that when the curl of the material is flattened they do not interfere with the layup (Figure 3-9).

8. Pressing

a. Press is preheated to 260ºC (500ºF) for the nylon and 190ºC (375ºF) for the polypropylene (Figure 3-10).

b. The tool with the layup is placed into the press making sure that none of the shims shift inside.

c. Press the tool with the hydraulic ram to achieve 1.0 MPa (~150 psi).

d. Allow the press to come back up to 260ºC (500ºF) for the nylon and 190ºC (375ºF) for polypropylene, and allow to consolidate for 15 minutes at these temperatures.

e. Ensure pressure remains constant at 1.0 MPa (~150 psi) for the entire consolidation cycle.

f. After the 15 minute consolidation time, shuttle the mold to a room temperature press, and apply 1.0 MPa (~150 psi) as the mold cools.

g. After the mold has cooled to below 120ºF, it can be removed from the room temperature press.

Figure 3-10: The mold is pressed to consolidate the thermoplastic material.

9. Removal of the Panel from the Tool

    a. Use a scraper or large screw driver to pry the two halves of the tool apart (Figure 3-11).

    b. Aluminum foil that is still attached to the plate can be removed by hand or with a razor blade (Figure 3-12).

    c. In one corner of the panel write: Date, Type of Material (PP or N6), and Number.

    d. Place the panel in the storage bag.

    e. Record the process in lab book and all deviations from the procedure.

Figure 3-11: The mold is opened.

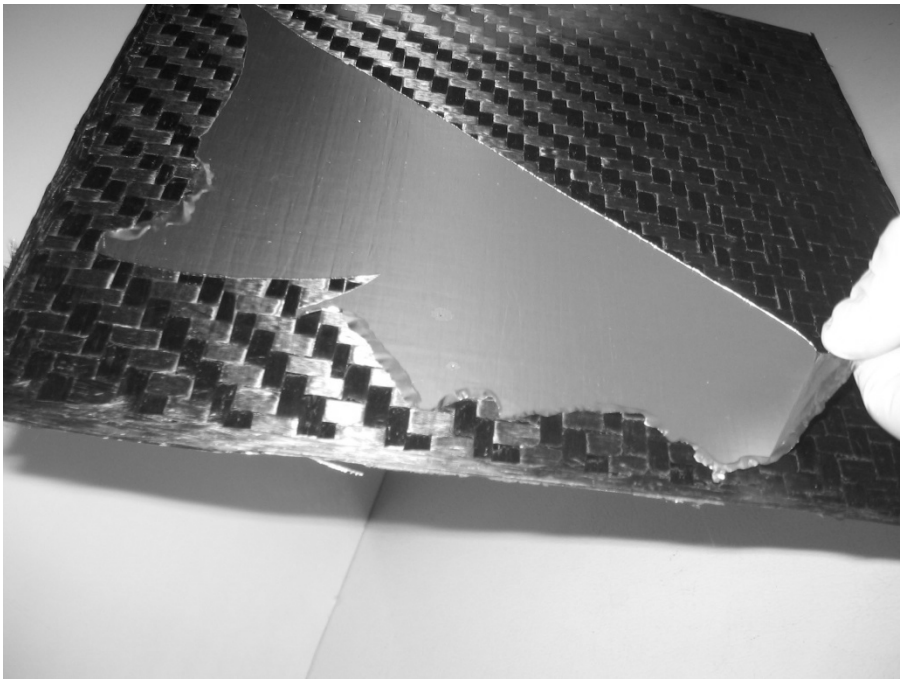

Figure 3-12: Excess aluminum foil is removed.

3.2.2 Contamination Issues

Imperative to bonding plates successfully is ensuring the plates are free of contaminants. Contamination of the surface can result in a barrier between the adhesive and the adherend, resulting in decreased bond strength. Contaminants of great concern are the same materials that are often used in mold releases and include fluorine and silicone based materials. These particular materials reduce friction and surface energy when they are included on the surface of the adherends, which is of benefit when de-molding and a hindrance when bonding. The manufacture of clean, contaminant-free adherends requires measures be taken to ensure a clean environment around the material and that only certain mold releases be used.

Initially, a tool was used that was well seasoned with PTFE mold release. This led to contamination of the bonding surface as was confirmed by poor bonding and X-ray Photoelectron Spectroscopy (XPS) performed at Ford Research Center. Based on these results, additional samples were made using a new aluminum plate as a tooling surface. A TFE film was used as a barrier and as a release layer. However, XPS analysis confirmed that high levels of fluorine (up to 7.9%) were still found on the plate surface as shown in Table 3-1. It was assumed that transfer of fluorine was occurring from the TFE film to the thermoplastic adherend.

Given the level of fluorine on the surface, a series of plates were made utilizing new aluminum tooling surfaces and zinc stearate as a mold release. Plates were manufactured with no mold release; however the thermoplastic bonded to the aluminum plates necessitating some level of mold release. XPS analysis was performed in the University of Utah Nanofabrication Laboratory. Results indicated, the use of new aluminum tooling

Table 3-1: Data from initial XPS testing.

	Elemental Composition--Atomic %									
Sample	**C**	**O**	**N**	**F**	**S**	**Si**	**K**	**Na**	**Cl**	**Al**
PP-2	89.3	5.9	-	3	0.79	-	-	1	-	-
PP-3	87.6	9.2	1.2	1.7	0.13	-	-	0.27	-	-
PP-4	74.8	17.7	-	-	-	5.1	-	0.4	0.47	1.5
PP-Bulk	97.9	2.1	-	-	-	-	-	-	-	-
N6-2	69.1	13.2	7.3	7.9	0.74	0.31	0.66	0.88	-	-

surface and zinc stearate eliminated the fluorine contaminant, and improved surface finish as shown in Table 3-2.

After an initial round of lap shear testing, the comparative bond strengths obtained for polypropylene in the initial qualitative testing were unsatisfactory. It was believed that the zinc stearate mold release was contaminating the surface of the polypropylene, resulting in the low comparative bond strengths. A Kapton film (polyolefin) was found to have the desirable characteristics of suitable release and low contamination for this application. Kapton films have been used as releases for higher processing temperature thermoplastics such as PEEK. It was found the Kapton would release from the polypropylene adequately but would not release from the nylon. Since the nylon showed excellent bond strength with the zinc stearate on aluminum foil, it was deemed not necessary to revise the release for the nylon. The polypropylene was inspected by XPS for and a reduction in zinc was found.

Table 3-2: XPS results utilizing new tooling and zinc stearate mold release.

Peak	Position	FWHM	Raw	Area	RSF	Atomic	Atomic	Mass
BE	(eV)	(eV)	(CPS)	Mass	Conc	%	Conc	%
Zn	2p	1022	3.982	39896.2	5.589	65.387	0.45	2.27
F	1s	689	1.822	17.5	1	18.998	0	0
O	1s	532	3.648	144893.8	0.78	15.999	10.64	13.07
Ca	2p	348	3.667	19175	1.833	40.078	0.62	1.92
C	1s	285	3.197	394655.9	0.278	12.011	86.18	79.51
Si	2s	153	3.206	4605	0.324	28.086	0.89	1.91
N	1s	401	2.82	9843.3	0.477	14.007	1.22	1.31

4 ADHESIVES AND SURFACE TREATMENTS

4.1 Introduction

In a bonded joint, the adhesive joins two surfaces often called adherends or substrates. An adhesive is generally considered a material that bonds or unites two adherends together such that they act as a unit and load is transferred through the joint. Most structural adhesives are thermosetting, meaning that they cross-link and thus increase the number of primary bonds when curing [7, 8]. Epoxies have historically been the most commonly used adhesive with composites. However, new chemistries have improved acrylics, cyanocrylates and urethanes for use in this industry.

Using the proper adhesive is only part of the solution when bonding composites and particularly thermoplastic composites. Surface treatments to increase surface tension can increase wet-out of adhesives increasing bond strength. In addition, surface treatments can remove contaminants that can result in a barrier between the adherend and adhesive causing low bond strength.

There are four common theories used to explain how adherends and adhesives are bonded together. Mechanical interlocking is the simplest and suggests that the adhesive fills into voids in the surface of the adherend and cures. Once it is cured, it cannot be pulled out of the voids unless the adhesive or the adherend fails. Surface treatments can remove contamination and open up these voids for this bonding to take place. In addition, treatments that mechanically change the surface also increase the surface area of interaction between the adherend and adhesive [7, 8].

Covalent bonding is a second theory that suggests that primary bonds occur between the adhesive and adherend during curing. For this to occur, chemical groups must cause a reaction at the interface of the materials. Electrostatic attraction is a third theory and suggests that the materials bonded together have an ionic attraction. Finally, acid-base interactions result in an interaction where one material gives up a hydrogen atom and the other accepts it [7, 8].

It is important to note that these theories are not completely established and much debate continues to surround them. No attempt is made to understand which type of bonding has occurred in this investigation. Instead, an understanding of failure type is deemed more important. Thus, failures are judged to be adhesive or cohesive. Adhesive failures occur between the adhesive/adherend interfaces and are considered unfavorable as the interface is the weakest point of the joint. Cohesive failures occur within the adhesive itself. In addition, failure within the adherend can occur. These are considered favorable because the bond strength is greater than the adhesive strength [5].

Below are a summary of the adhesives and surface treatments investigated and an outline of the decision process used in the selection process.

4.2 Overview of Adhesives

In a previous study conducted by the University of Utah [2] only thermosetting structural adhesives were considered. This resulted in the identification of four types of adhesives: epoxies, acrylics, cyanoacrylates, and urethanes. However during testing it was found that only three adhesives were practical for use with this investigation: epoxies, acrylics, and urethanes. The adhesives used in this investigation are shown in Table 4-1.

Table 4-1: List of adhesives, adhesive type and comments regarding application of those used in this investigation.

Supplier/Adhesive	Adhesive Type	Comments
Lord 320/322 [24]	toughened epoxy	Moderate difficulty to use and spread. High viscosity
Lord 7542 [24]	urethane	Easy to use and spread. Slight noxious odor.
3M 8239 [25]	urethane	Difficult to use due to short work time (~1 min). Slight noxious odor
Dow LESA [26]	acrylic	Easy to use and spread. Highly noxious odor
Dow LESA w/ Betaprime^{TM} 5404A [26] primer	acrylic	Easy to use and spread. Highly noxious odor

4.3 Surface Treatments

Surface treatments were divided into two groups: in-house and specialty treatments. The in-house treatments are those that do not require highly-specialized processing equipment. The only in-house treatment investigated was acid washing. The specialty treatments require highly-specialized equipment which in each case investigated requires significant capital investment. Specialty treatments investigated include ATmaP® flame, Openair® plasma, and Sulfonation treatments. Each surface treatment method is summarized below.

4.3.1 Acid Washing

The acid wash treatment was a simple cleaning with a 3% phosphoric acid solution to potentially remove contaminants. This is a commonly used method for removing small amounts of zinc stearate left on the surface after manufacture. Adherends were

completely submerged (Figure 4-1) in the 3% phosphoric acid solution for approximately 5 minutes before being rinsed clean with distilled water. Adherends were bonded within 24 hours of treatment.

4.3.2 Openair® Plasma

A plasma is a higher energy state of matter composed of charged particles. It is what comprises the sun, stars and other objects seen outside of our solar system. Here on Earth, plasma can be found in neon lights, flames and electric discharges. While these sources are often associated with heat, the temperature of plasma is often below the temperature of the same material in a gaseous phase. Thus, a plasma treatment can be performed at a lower temperature thereby reducing potentially negative effects of heat.

Openair® is a trademarked name owned by Plasmatreat North American Inc. Previously, plasma treatment had existed but it had to be contained within a chamber,

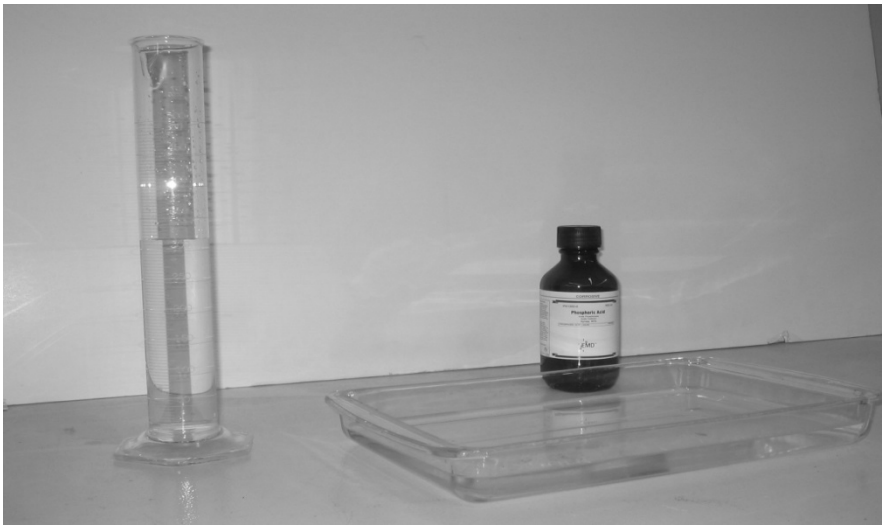

Figure 4-1: Acid washing comprised of submersion in a 3% phosphoric acid solution for approximately 5 minutes.

making treatment difficult for large or complexly shaped parts. The Openair® method uses electricity to excite molecules in the air, thereby generating plasma. This plasma removes contaminants, static electricity and dust by oxidizing these compounds. The exposed polymer chains of the thermoplastic are also affected and the ends are broken off and replaced with highly reactive –OH and –NH groups. This increases the wettability and surface energy which potentially increases the bond strength of the treated adherend. The Openair® system utilizes a robot arm to move the nozzle that projects the plasma (Figure 4-2), allowing for varying speed and hence time of exposure of the surface being treated. In addition, the amount of plasma, or intensity, can be varied [27].

Adherends were treated courtesy of Ford RIC of Dearborn, MI. Five different parameter sets were used where speed and intensity of the plasma beam were varied. In all cases, adherends were bonded within 24 hours of treatment to remove fade as an unwanted potential parameter.

4.3.3 ATmaP® Flame

Flame treatment utilizes combustion to burn contaminants, increase surface energy and improve wettability. Historically, flames of most all types have been used though significant advances have been made in the past decade. The ATmaP® flame Technology is a trademarked process by FTS Technologies of Flint, MI. The ATmaP® delivers a highly controlled flame that burns with an oxygen content of 0.2-1.2% oxygen. A water-borne diimine solution is evaporated into the flame and interacts with the surface to replace lower energy molecules that are removed from the plasma contained in the flame. Nitrogen is used to encompass the flame which results in the surface becoming

Figure 4-2: The Openair® plasma machine used by Ford RIC to treat adherends.

polarized. The system allows for each of these parameters to be controlled in addition to flame dwell time through the use of a computer-controlled robot arm.

Adherends were treated courtesy of FTS Technologies. FTS performed a series of tests to determine the ideal treatment parameters based on contact angle measurements. Contact angle measures the angle of various fluids dropped onto a surface. As the angle between the droplet and surface decreases, the surface is considered to have higher wettability and therefore have higher bond strength. Even though contact angle is not a

direct correlation to bond strength, it is assumed that smaller angles result in better bond strength. Even though previous research by FTS has shown that fade does not occur, the treated adherends were bonded within 24 hours of treatment to remove fade as an unwanted potential parameter [28].

4.3.4 Surface Activation (Sulfonation)

Surface Activation is a modification of traditional sulfonation. It is the exposure to specific concentrations of sulfur trioxide gas, thus attaching sulfur and oxygen atoms to the surface of the adherend. Next, the sulfonate is made chemically inert by treating the surface with a neutralizing agent. The result is a chemically modified polar surface layer that is up to 25 microns thick. The exposure takes place inside of the chamber filled with sulfur trioxide where most of the sulfur trioxide is recaptured, filtered and reused.

The Surface Activation was performed by Surface Activation Technologies of Troy, MI. Exposure time was varied from 3 to over 10 minutes. Given the depth of the treatment, fade was not considered to be an issue [29]. However, adherends were bonded within 24 hours of treatment.

5 LAP SHEAR TESTING

5.1 Introduction

The single lap shear test was used to identify the adhesive and surface treatment combinations with the best adhesion. It was selected due to its relative quickness, expense and ease of manufacture.

In this investigation, lap joints were tested in tension at room temperature following procedure ASTM D 3163 [30]. Load versus displacement curves were generated for each test and compared to determine consistency of the bond strength between replicate specimens. The peak load was determined and the bonded area was measured for each parameter group to be used to calculate the comparative bond strength.

5.2 Background

The lap shear joint test is a commonly used adhesive test. Specimens are simple to build, test, and readily resemble the geometry of many practical joints. Even though different configurations can be used, the most common for rigid plastic adherends is the single lap test outlined in the ASTM designation D 3163 shown in Figure 5-1. This test method is titled “Determining the Strength of Adhesively Bonded Rigid Plastic Lap Shear Joints in Shear by Tension Loading” [30].

It must be noted that although the test is called lap “shear” the failure is usually related to the tensile stresses rather than strictly the shear stresses. Typically, the apparent adhesive strength or lap shear strength is reported as the ratio of the load at

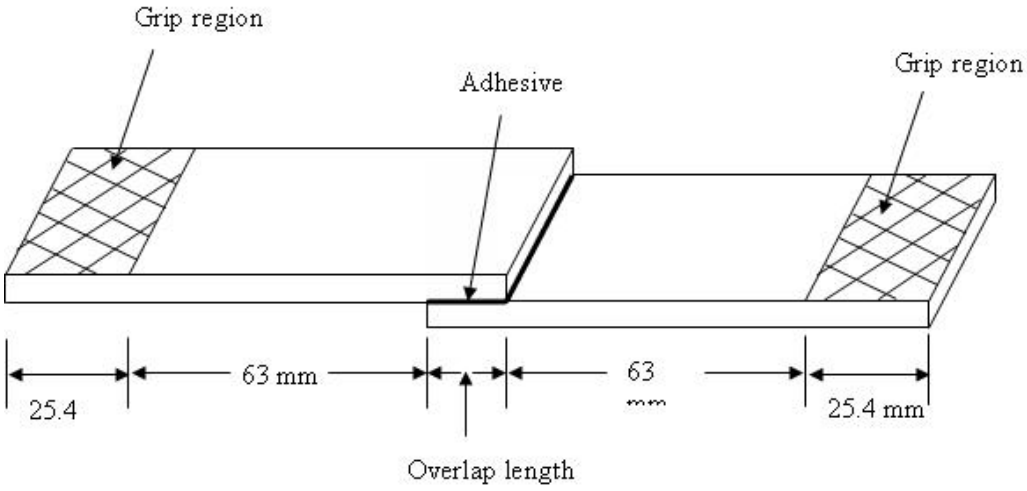

Figure 5-1: The single lap shear test configuration outlined in ASTM D 3163**.**

failure to the area of overlap. This value is often reported in adhesive handbooks and on data sheets supplied by adhesive manufacturers even though the value is often different from the maximum stress. This has led to the use of overly simplified design rules such as average stress criteria that can lead to inaccurate assumed bond strength. Often left out are effects resulting from adherend thickness, adhesive bond thickness and overlap length, which Powers and Trzaskos determined affected bond strength significantly [10]. This test can be useful for comparison of the parameter groups in this investigation, but the results must be interpreted with caution. Thus, the term "comparative" bond strength is used to imply that this value should be used only for comparison within this investigation. For more information regarding the known issues associated with the single lap shear joint test, the reader is referred to ASTM D 4896 [31].

5.3 Methods

For lap shear testing, the test specimen geometry was selected in accordance with ASTM D 3163. The manufacturing procedure of the thermoplastic plates outlined in

Chapter 3 was followed. An acid wash was performed prior to all surface treatments, in an attempt to remove additional contaminants. The specimens were 4 plies thick and 25.4 mm (1.0 in) wide. Each specimen was approximately 101.6 mm (4.0 in) long and a bond length, L, was chosen to be 12.3 mm (0.5 in). Bond thickness was controlled by placing 0.51 mm (0.020 in) thick wires in the bond area. Fixtures were machined to hold the specimen plates at the proper places with respect to each other and pins were used to ensure proper placement. Plates at least 127 mm (5 in) wide bonded for each parameter group and all samples tested were cut from the same larger plate. The plates were held in the fixtures for at least 12 hours which at least doubled the hardening time for each adhesive. After removal from the fixtures, the specimens were cured at room temperature for at least 48 hours before they were cut, ensuring that a complete and consistent cure was achieved.

A minimum of three specimens were tested for each test parameter group resulting in over 60 tests. In several cases, additional specimens were tested if one of the other specimens was damaged when handled or loaded into the test frame. Specimens were loaded into an Instron 4303 tensile testing frame with a 5 kip load cell. A constant displacement rate of 1.27 mm/min (0.050 in/min) was used. Load versus displacement curves, bond area, peak load, and failure type were noted for each specimen tested. The bond area and peak load were used to calculate comparative bond strength for each specimen and average stress for each parameter group. These bond strengths were then used to compare the different parameter groups and assess which parameter group achieved highest bond strength. The calculated strengths are not intended for use in

design, but only as a reference to compare the different parameter groups within this investigation.

5.4 Results and Discussion

The different parameters were tested and the data are summarized in Tables 5-1 and 5-2. The data from Tables 5-1 and 5-2 are also presented graphically to compare average comparative bond strength for nylon and polypropylene, respectively. As seen in Figure 5-2 the parameter groups involving nylon achieved the highest comparative bond strength. The average strengths of the polypropylene parameter groups were considerably lower than the nylon with the exception of Openair® plasma treated Dow LESA with Betaprime™ primer. It should also be noted that in general higher strength parameter groups had a smaller relative variation.

Nylon not only outperformed polypropylene, it has the five highest comparative bond strength parameters. However, differences between these parameter groups are not statistically significant as shown in Figure 5-2. The Lord 320/322 epoxy had four of the five highest overall comparative bond strengths. It is also interesting to note that the two highest comparative bond strengths were achieved with the acid wash surface treatment.

The comparative bond strength of nearly all the polypropylene candidates increased with the removal of the zinc stearate as the mold release as shown in Figure 5-2 with the exception of the Openair® plasma 3M8239.

It is evident from Figure 5-2 that the polypropylene comparative bond strength parameters can be divided into five distinct levels of strength. Openair® plasma LESA with Betaprime™ 5404A primer is the only member that occupies the highest strength

Table 5-1: Nylon data collected and calculated from lap shear testing.

Combination	Bonded Area (m^2)	Peak Force (N)	Bond Strength (MPa)	Ave. Bond Strength (MPa)	Standard Deviation (MPa)	Failure Type
Acid Wash Nylon/Lord 320/322	2.68E-04	3407	12.7	12.2	0.6	cohesive
	2.77E-04	3428	12.4			
	2.78E-04	3181	11.5			
Acid Wash Nylon/3M 8239	2.68E-04	3181	11.9	11.6	0.2	cohesive w/ fiber pull
	2.83E-04	3280	11.6			
	2.78E-04	3199	11.5			
ATmaP® Nylon/Lord 320/322	3.04E-04	3433	11.3	11.6	0.3	cohesive
	2.84E-04	3342	11.8			
	2.82E-04	3342	11.9			
Openair® Nylon/Lord 320/322	2.53E-04	2877	11.4	11.3	1.4	cohesive
	2.46E-04	3128	12.7			
	2.57E-04	2559	9.9			
Surface Act Nylon/Lord 320/322	2.87E-04	3117	10.9	10.2	0.7	cohesive w/ fiber pull
	2.86E-04	2963	10.4			
	2.88E-04	2732	9.5			
Openair® Nylon/3M 8239	2.79E-04	613	2.2	6.3	3.0	mixed
	2.81E-04	2382	8.5			
	2.76E-04	2404	8.7			
	2.82E-04	1604	5.7			
Surface Act Polypro/Lord 7542 w/ Zinc	3.04E-04	700	2.3	2.8	0.7	cohesive w/ fiber pull
	2.99E-04	706	2.4			
	3.03E-04	1092	3.6			
Surface Act Polypro/Lord 320/322 w/ Zinc	2.61E-04	791	3.0	2.5	0.8	cohesive w/ fiber pull
	2.68E-04	513	1.9			
	2.78E-04	n/a	n/a			
Openair® Nylon/Bondmaster M1315	2.84E-04	428	1.5	2.4	1.1	adhesive
	2.82E-04	620	2.2			
	2.80E-04	1002	3.6			
Openair® Polypro/3M 8239 w/ Zinc	2.93E-04	407	1.4	2.2	0.7	adhesive
	3.11E-04	910	2.9			
	3.00E-04	793	2.6			
	3.18E-04	613	1.9			

Table 5-2: Polypropylene data collected and calculated from lap shear testing.

Combination	Bond Area (m^2)	Peak Load (N)	Stress (MPa)	Average Stress (MPa)	Failure Type
Openair® Polypro Dow LESA w/Primer	2.87E-04	3262	11.4	10.0	cohesive w/ fiber pull
	2.93E-04	2886	9.9		
	2.91E-04	2872	9.9		
	3.00E-04	2668	8.9		
Surface Act 481 Polypro Dow LESA	2.94E-04	2210	7.5	7.4	adhesive
	2.95E-04	1570	5.3		
	2.87E-04	2342	8.2		
	2.88E-04	2531	8.8		
Surface Act 482 Polypro Dow LESA w/Primer	2.95E-04	1802	6.1	6.7	adhesive w/ fiber pull
	2.79E-04	2175	7.8		
	2.82E-04	1898	6.7		
	2.89E-04	1784	6.2		
Surface Act 482 Polypro Lord 320/322	2.89E-04	1690	5.8	6.5	cohesive w/ fiber pull
	2.82E-04	1985	7.0		
	2.87E-04	1953	6.8		
	2.91E-04	1879	6.4		
Surface Act 482 Polypro Lord 7542	2.86E-04	1714	6.0	6.5	adhesive
	2.82E-04	1647	5.8		
	2.91E-04	2054	7.0		
	2.97E-04	2141	7.2		
Surface Act 483 Polypro Dow LESA	2.89E-04	2378	8.2	6.2	fiber pull
	2.78E-04	1982	7.1		
	2.80E-04	1463	5.2		
	2.64E-04	1112	4.2		
Surface Act 481 Polypro Dow LESA w/Primer	2.83E-04	1528	5.4	6.1	fiber pull
	2.87E-04	1751	6.1		
	2.84E-04	1919	6.8		
Surface Act 482 Polypro LESA	2.87E-04	1496	5.2	5.1	adhesive w/ fiber pull
	2.83E-04	1502	5.3		
	2.83E-04	1338	4.7		
	2.86E-04	1455	5.1		
ATmaP® Polypro Dow LESA w/Primer	2.83E-04	1473	5.2	4.7	adhesive w/ fiber pull
	2.87E-04	974	3.4		
	2.87E-04	1563	5.5		
	2.97E-04	n/a	n/a		
Openair® Polypro Dow LESA	2.97E-04	1148	3.9	4.3	adhesive w/ fiber pull
	3.07E-04	1416	4.6		
	3.17E-04	1319	4.2		
	3.28E-04	1513	4.6		
Surface Act 483 Polypro Dow LESA w/Primer	3.01E-04	854	2.8	2.6	adhesive
	2.91E-04	894	3.1		
	2.93E-04	510	1.7		
Openair® Polypro 3M8239	2.89E-04	250	0.9	0.9	adhesive
	2.87E-04	275	1.0		

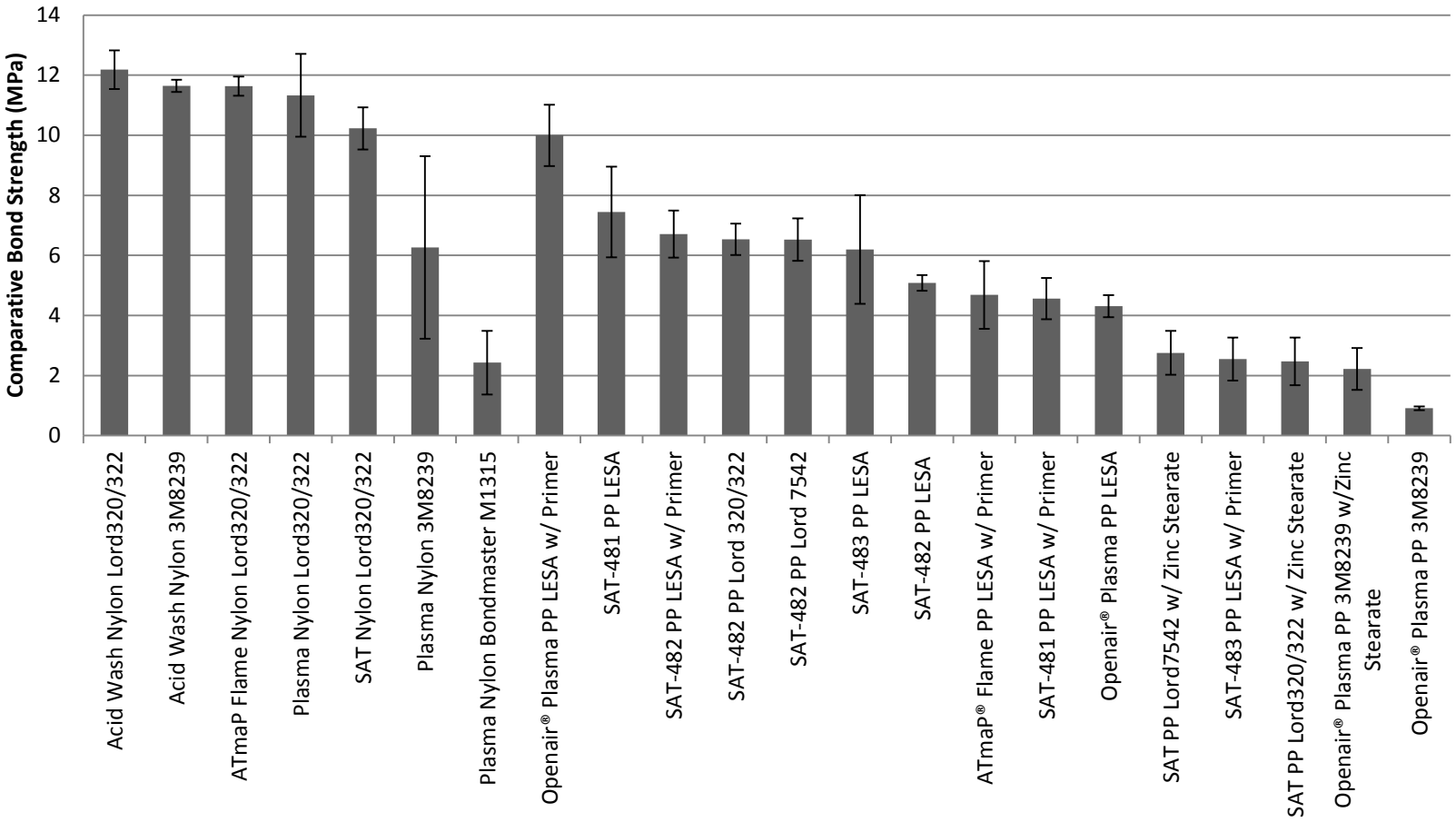

Figure 5-2: Comparative bond strength of each specimen tested using the lap shear test.

level. There is then a step down in strength to the next level, which has five members from Surface Activated Technologies 481 LESA to Surface Activated Technologies 483 LESA. The next lower strength level has four members from Surface Activate Technologies 482 LESA to Openair® plasma LESA. The fourth strength level has four members and contains all three previous parameters which were manufactured with the zinc stearate mold release. The fifth and lowest strength level has only one member, Openair® plasma with 3M 8239.

5.5 Summary

The highest scoring parameter groups from the previous investigation through spot adhesion testing [2] were tested quantitatively using the lap shear test outlined in ASTM D 3163. Specimens were fabricated for each of these high scoring parameter groups. Peak load was established and average bond strength—referred to as comparative bond strength—was calculated to be used as a comparative measure within this investigation.

From the lap shear test results, the previous conclusion that the nylon thermoplastic composite is capable of higher bond strengths than the polypropylene thermoplastic composites was again confirmed. In addition, the epoxy adhesive achieved higher strengths and more consistent results than the other adhesives investigated. A method for polypropylene manufacture for adequate comparative bond strength was achieved.

6 FRACTURE TOUGHNESS TESTING

6.1 Introduction

Peel and cleavage tests can be useful for characterizing different adhesive and surface treatment properties. Peel testing was not included due to the more compliant adherends to be used. Cleavage testing was performed, due to its relative quickness, expense and ease of manufacture.

In this investigation, cleavage specimens are tested according to ASTM D 3433 [32]. Load versus displacement curves were generated for each test and from that the fracture toughness was calculated.

6.2 Background

Cleavage tests are designed with an intentional, nonuniform distribution of stress. These tests differ from peel tests in that both adherends are relatively rigid, resulting in an approximately 0^{o} peel angle. While ASTM has standardized several cleavage tests for adhesives, the one most relevant to this proposed study is that described in ASTM D 3433, "Standard Test Method for Fracture Strength in Cleavage of Adhesives in Bonded Metal Joints." This test method uses a longer cleavage specimen composed of two long slender rectangular strips bonded together over part of their length as shown in Figure 6-1.

The adherends require a certain stiffness and strength, so they can bend through a certain angle without failing. Near the end of the unbonded section of the adherends, a

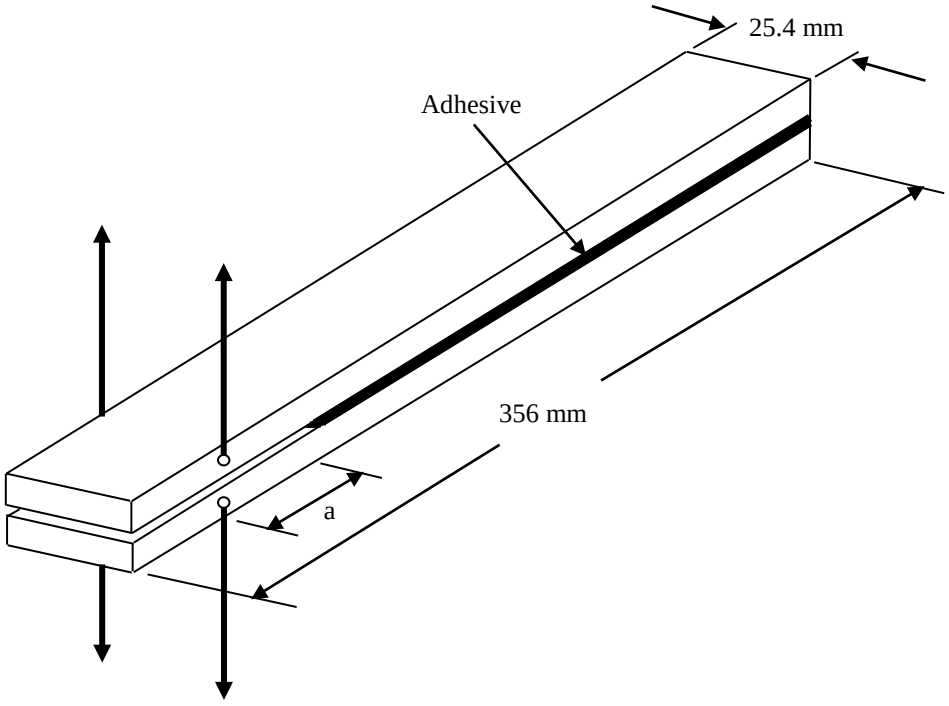

Figure 6-1: Flat adherend cleavage specimen for determining fracture toughness

flexible wire is attached. These wires are clamped in the grips of the tensile testing machine. As the specimen is subjected to tensile loading, the wires separate the unbonded section, subjecting the bondline to tension and bending. This result of peak force per specimen width is of little use in the design of joints that differ in detail from the specimen and loading configuration. However, this joint may be analyzed with a fracture mechanics perspective.

The fracture mechanics approach considers the adhesive joint as a system in which failure or growth of the crack requires that the stresses at the crack tip be sufficient to break bonds, and its analysis involves an energy balance. This means that a crack can grow only if sufficient energy is released from the stress field that will balance with the amount of energy required to create the new crack surface as the fractured region enlarges. The critical value of this energy release rate is referred to by various names,

including the adhesive fracture energy, adhesive fracture toughness, and work of adhesion. Here G_{1c} will be used to represent this critical energy release rate from ASTM D 3433 [32].

$$G_{1C} = \frac{4L^2(\max)(3a^2 + h^2)}{EB^2h^3} \tag{6.1}$$

where,

G_{1C} is the fracture toughness (J/m^2)

$L(\max)$= load to start the crack (N)

E = tensile modulus of adherend (MPa)

B = specimen width (mm)

a = crack length (mm)

h = thickness of adherend, normal to plane of bonding (mm)

The word “adhesion” is dropped from the comparable term when considering cohesive failure.

6.3 Methods

For cleavage testing, the test specimen geometry was selected in accordance with ASTM D 3433. The manufacturing procedure of the thermoplastic plates outlined in Chapter 3 was followed. An acid wash was performed prior to all surface treatments, in an attempt to remove additional contaminants. The specimens were 8 plies thick and 25.4 mm (1.0 in) wide. Each specimen was approximately 127 mm (5.0 in) long and the initial crack length, a, was chosen to be 12.3 mm (0.5 in). Bond thickness was controlled by placing 0.51 mm (0.020 in) thick wires in the bond area. Fixtures were machined to hold the specimen plates at the proper places with respect to each other and pins were

used to ensure proper placement. Plates at least 127 mm (5 in) wide were bonded for each parameter group and all samples tested were cut from the same larger plate. The plates were held in the fixtures for at least 24 hours which at least doubled the hardening time for each adhesive. After removal from the fixtures, the specimens were cured at room temperature for at least 48 hours before they were cut, ensuring that a complete and consistent cure was achieved.

A minimum of three specimens were tested for each test parameter group. In several cases, additional specimens were tested if one of the other specimens was damaged when handled or loaded into the test frame. Specimens were loaded into an Instron 4303 tensile testing frame with a 5 kip load cell. A constant displacement rate of 12.7 mm/min (0.50 in/min) was used. As the crack propagated along the length of the specimen, crack length was noted and associated with the load versus displacement curves to calculate G_{1C} according to ASTM D 3433 using Equation 6.1.

6.4 Results and Discussion

The data from the cleavage testing were more involved than the lap shear testing for quantifying the G_{1c} of the particular adherend adhesive combinations. Each sample represents three to five G_{1c} calculations along its length as the crack propagated. Coupling this with the three specimens per combination results in a total of 9 to 15 G_{1c} calculations per combination.

The data for nylon are presented in Table 6-1. The data were also compiled into Figure 6-2 for easier graphical reference. Nylon had overall higher G_{1c} values than polypropylene as seen in Figure 6-2. This result was expected due to the higher comparative bond strengths achieved with nylon. Within the nylon adherends, the 3M

8239 urethane based adhesive outperformed the Lord 320/322 epoxy based adhesive. While both adhesives achieved excellent comparative bond strengths, the urethane adhesive had a much greater fracture toughness over the epoxy adhesives which are generally more brittle.

The data for polypropylene are presented in Table 6-2. Polypropylene was outperformed by nylon due to the reduced bond strength between the adhesive and the adherend. Polypropylene failures were mainly between the adhesive and the adherend and were not cohesive failures within the adhesive itself. The fracture energies measured were mainly between the polypropylene adherend and the adhesive.

Table 6-1: Nylon fracture toughness data.

Combination	Sample	G1c (J/m^2)	Std Deviation (J/m^2)	Avg G1c (J/m^2)
Openair® Nylon 3M 8239	1	554.44	446.78	1223.40
	2	1372.79	902.64	
	3	1742.96	682.22	
Surface Act. Nylon Lord 320/322	1	912.41	317.25	878.67
	2	869.57	196.19	
	3	854.04	119.60	
ATmaP® Nylon Lord 320/322	1	787.69	117.60	852.45
	2	812.19	46.98	
	3	957.46	116.66	
Acid Wash Nylon Lord 320/322	1	774.07	69.71	834.29
	2	834.48	101.67	
	3	894.32	141.41	
Openair® Nylon Lord 320/322	1	567.40	63.46	762.92
	2	707.60	101.50	
	3	1013.77	244.10	

Table 6-2: Polypropylene fracture toughness data.

Combination	Sample	G1c (J/m^2)	Std Deviation (J/m^2)	Avg G1c (J/m^2)
Surface Act. 482 Polypro Lord 7542	1	265.66	58.84	462.04
	2	611.55	172.86	
	3	638.67	150.52	
	4	332.28	132.04	
Surface Act. 482 Polypro Lord 320/322	1	340.52	75.95	434.20
	2	500.99	130.61	
	3	544.89	98.84	
	4	350.40	61.86	
Openair® Polypro Dow LESA w/Primer	1	205.10	42.73	378.74
	2	340.35	122.60	
	3	590.76	206.58	
Surface Act. 483 Polypro Dow LESA	1	187.94	38.79	357.79
	2	666.69	166.05	
	3	305.60	31.53	
	4	270.92	74.89	
Surface Act. 482 Polypro Dow LESA	1	314.61	76.80	318.39
	2	324.76	46.73	
	3	206.56	82.30	
	4	427.62	355.83	
Surface Act. 482 Polypro Dow LESA w/Primer	1	290.49	66.00	298.73
	2	361.65	148.39	
	3	244.05	95.63	
Surface Act. 481 Polypro Dow LESA w/Primer	1	161.53	95.73	218.94
	2	264.29	94.52	
	3	230.99	27.76	
Surface Act. 483 Polypro Dow LESA w/Primer	1	204.34	30.60	218.44
	2	210.04	99.26	
	3	240.93	43.03	
Openair® Polypro 3M 8239	1	179.13	96.10	196.99
	2	218.15	7.96	
	3	193.67	95.09	
Surface Act. 481 Polypro Dow LESA	1	128.40	27.24	159.57
	2	231.01	95.95	
	3	115.15	37.83	
	4	163.73	15.34	
Openair® Polypro Dow LESA	1	57.04	9.31	93.65
	2	124.72	38.29	
	3	80.22	12.47	
	4	112.62	35.70	

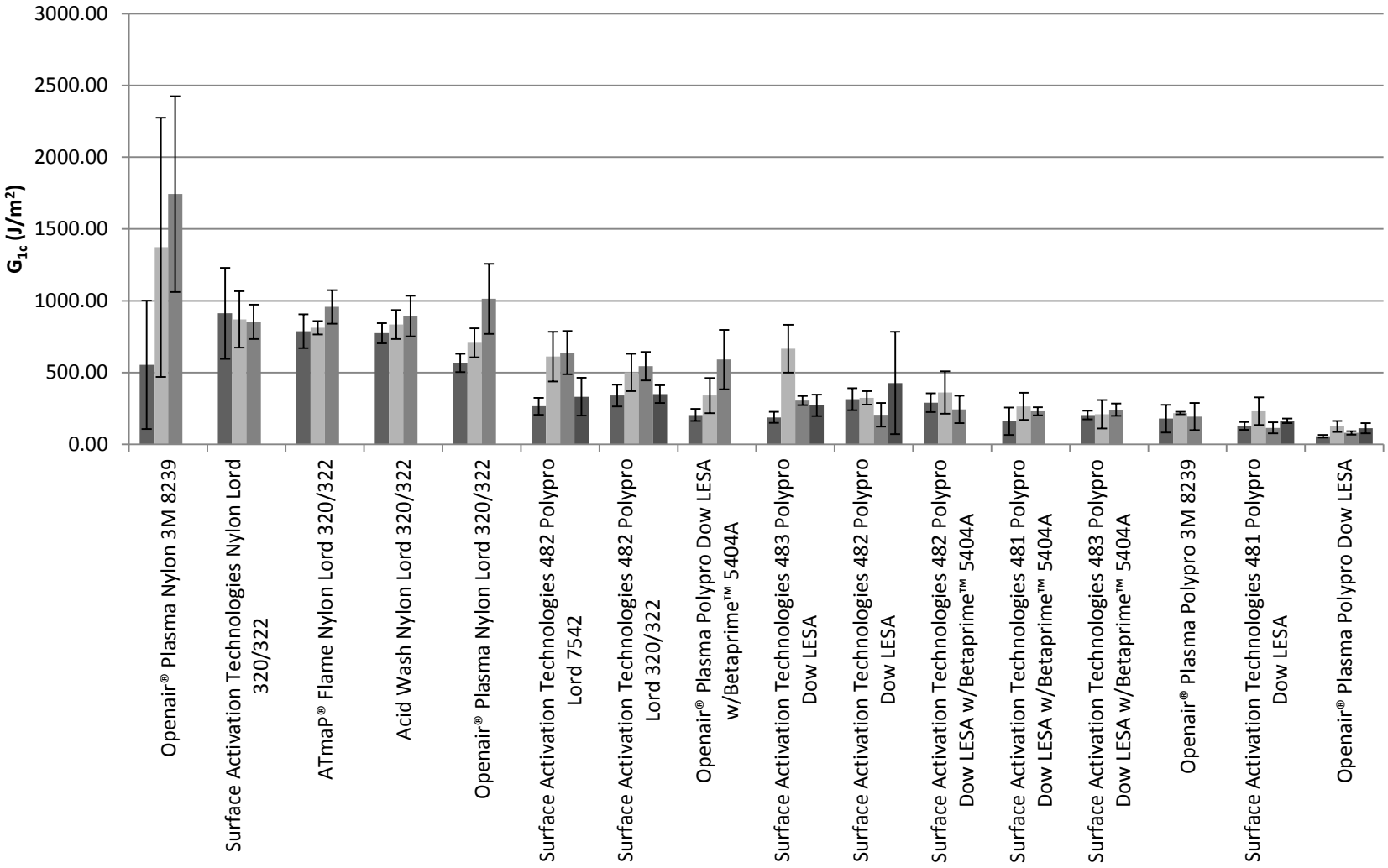

Figure 6-2 : Fracture toughness energies for all tested parameters

6.5 Summary

The highest scoring parameter groups from the previous investigation through spot adhesion testing [2] were tested quantitatively using the cleavage test outlined in ASTM D 3433. Specimens were fabricated for each of these high scoring parameter groups. The fracture toughness of these specimens was calculated to be used as a comparative measure within this investigation.

From the cleavage test results, the previous conclusion that the nylon thermoplastic composite is capable of higher bond strengths than the polypropylene thermoplastics composites was again confirmed. In addition, the urethane adhesive had higher fracture toughness than did the epoxy adhesive.

7 ENVIRONMENTAL TESTING

7.1 Intoduction

In order to determine the effectiveness of different adhesive, surface treatment and aherend combinations under actual working conditions, it was deemed necessary to expose them to various environmental conditions. Input was sought from the ACC, and the acceptable environmental parameters were selected.

7.2 Background

The top performing adherend adhesive combinations of acid washed nylon thermoplastic with Lord 320/322 adhesive and Openair® plasma polypropylene with Dow LESA and Betaprime^{TM} 5404A primer were selected for the additional environmental testing. The three environmental parameters decided upon for the environmental tests were a hot test of 80ºC (176ºF), a cold test of -40ºC (-40ºF), and a hot/wet test of 50ºC (122ºF) and 85% relative humidity.

7.3 Methods

For lap shear testing, the test specimen geometry was selected in accordance with ASTM D 3163. The manufacturing procedure of the thermoplastic plates outlined in Chapter 3 was followed. An acid wash was performed prior to all surface treatments, in an attempt to remove additional contaminants. The specimens were 4 plies thick and 25.4 mm (1.0 in) wide. Each specimen was approximately 101.6 mm (4.0 in) long and a bond length, L, was chosen to be 12.3 mm (0.5 in). Bond thickness was controlled by

placing 0.51 mm (0.020 in) thick wires in the bond area. Fixtures were machined to hold the specimen plates at the proper places with respect to each other and pins were used to ensure proper placement. Plates at least 127 mm (5.0 in) wide were bonded for each parameter group and all samples tested were cut from the same larger plate. The plates were held in the fixtures for at least 12 hours which at least doubled the hardening time for each adhesive. After removal from the fixtures, the specimens were cured at room temperature for at least 48 hours before they were cut, ensuring that a complete and consistent cure was achieved.

The methods for the hot and cold tests are analogous except for the temperatures implemented. All specimens to be tested for the respective test were placed in the base of the test chamber. This was to ensure the specimens would be at the same temperature as the test chamber. The test chamber was turned on and set to the proper temperature. A thermocouple was placed inside the test chamber to ensure the proper temperature was reached. After the proper temperature had been reached, the test chamber was opened and a specimen was loaded into the grips. The test chamber was closed again and a 5 min. dwell time was used to allow the test chamber to return to the proper temperature.

The hot/wet test consisted of a exposing the specimens to a 50ºC (122ºF) and 85% relative humidity environment until the specimens stopped gaining weight. Before testing, they were placed in a 23ºC (73ºF) and 50% relative humidity environment for one hour to “dry out” then tested at room temperature.

A minimum of three specimens were tested for each test parameter group. In several cases, additional specimens were tested if one of the other specimens was damaged when handled or loaded into the test frame. Specimens were loaded into an Instron 4303

tensile testing frame with a 5 kip load cell. A constant displacement rate of 1.27 mm/min (0.050 in/min) was used. Load versus displacement curves, bond area, peak load, and failure type were noted for each specimen tested. The bond area and peak load were used to calculate comparative bond strength for each specimen and average stress for each parameter group. These bond strengths were then used to compare the different parameter groups and assess which parameter group achieved highest bond strength.

7.4 Results and Discussion

7.4.1 Acid Washed Nylon Lord 320/322

A graphical comparison of the different environmental parameters is shown in Figure 7-1. The parameter group of acid washed nylon thermoplastic adherends with Lord 320/322 adhesive at -40ºC (-40ºF) had an average comparative bond strength of 12.0 MPa (1.7 ksi). The failure modes at -40ºC (-40ºF) were primarily cohesive and fiber/matrix failures. At 80ºC (176ºF), the specimen had an average comparative bond strength of 1.8 MPa (0.27 ksi). The failure mode at 80ºC (176ºF) was cohesive. The adhesive at the elevated temperature had been softened and was no longer structurally sound, as evidenced by the cohesive failure with a very low strength. A cohesive failure is representative of achieving the highest bond strength to the adherend. At the 50ºC (122ºF) and 85% relative humidity, the specimen had an average comparative bond strength of 7.7 MPa (1.1 ksi). The reduction in strength for the hot/wet test suggests there is some reduction in strength due to temperature and humidity.

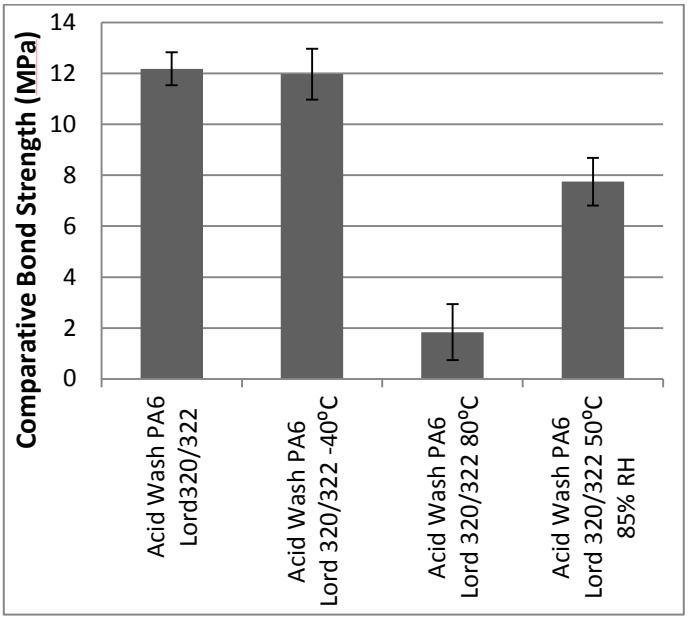

Figure 7-1: Comparative bond strength for acid wash nylon with Lord 320/322 adhesive under different environmental conditions.

7.4.2 Openair® Plasma Polypropylene Dow LESA with Betamate™ 5404A Primer

A graphical comparison of the different environmental parameters is shown in Figure 7-2. The parameter group of Openair® plasma polypropylene thermoplastic adherends with Dow LESA adhesive with Betamate™ 5404A primer at -40ºC (-40ºF) had an average comparative bond strength of 5.9 MPa (0.86 ksi). The failure modes observed at -40ºC (-40ºF) were adhesive, cohesive and fiber/matrix interface failures. At 80ºC (176ºF), the specimen had an average comparative bond strength of 1.9 MPa (0.27 ksi). The failure modes at 80ºC were adhesive and fiber/matrix interface failures. At the 50ºC (122ºF) and 85% relative humidity, the specimen had an average comparative bond strength of 3.9 MPa (0.57 ksi).

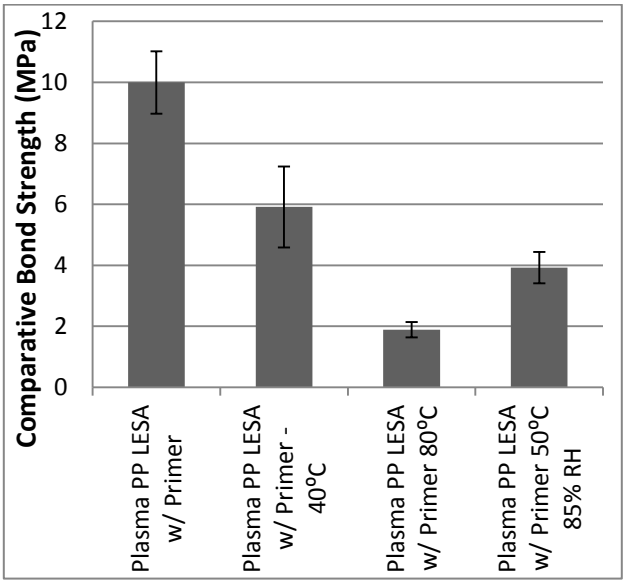

Figure 7-2: Comparative bond strength for Openair® plasma polypropylene with Dow LESA with Betamate 5404A primer under different environmental conditions.

8 FIBER REINFORCEMENT TESTING

8.1 Introduction

In order to determine the effectiveness of different adhesive, surface treatment and adherend combinations, an investigation of the fiber reinforcement was conducted. Input was sought from the ACC, and the best performing combinations with carbon reinforcement were selected for further testing with glass reinforcement.

8.2 Background

The top performing adherend/adhesive combinations for nylon were selected as acid washed with Lord 320/322 and 3M 8239. The top performing adherend adhesive combinations for polypropylene were selected as Openair® plasma with Dow LESA and Betaprime™ 5404A primer and Surface Activation Technologies 482 with Dow LESA and Betaprime™ 5404A primer.

8.3 Methods

For lap shear testing, the test specimen geometry was selected in accordance with ASTM D 3163. The manufacturing procedure of the thermoplastic plates outlined in Chapter 3 was followed. An acid wash was performed prior to all surface treatments, in an attempt to remove additional contaminants. The specimens were 4 plies thick and 25.4 mm (1.0 in) wide. Each specimen was approximately 101.6 mm (4.0 in) long and a bond length, L, was chosen to be 12.3 mm (0.5 in). Bond thickness was controlled by placing 0.51 mm (0.020 in) thick wires in the bond area. Fixtures were machined to hold

the specimen plates at the proper places with respect to each other and pins were used to ensure proper placement. Plates at least 127 mm (5.0 in) wide were bonded for each parameter group and all samples tested were cut from the same larger plate. The plates were held in the fixtures for at least 12 hours which at least doubled the hardening time for each adhesive. After removal from the fixtures, the specimens were cured at room temperature for at least 48 hours before they were cut, ensuring that complete and consistent cure was achieved.

A minimum of three specimens were tested for each test parameter group. In several cases, additional specimens were tested if one of the other specimens was damaged when handled or loaded into the test frame. Specimens were loaded into an Instron 4303 tensile testing frame with a 5 kip load cell. A constant displacement rate of 1.27 mm/min (0.050 in/min) was used. Load versus displacement curves, bond area, peak load, and failure type were noted for each specimen tested. The bond area and peak load were used to calculate comparative bond strength for each specimen and average stress for each parameter group. These bond strengths were then used to compare the different parameter groups and assess which parameter group achieved highest bond strength. The calculated strengths are not intended for use in design, but only as a reference to compare the different parameter groups within this investigation.

8.4 Results and Discussion

8.4.1 Carbon to Glass Reinforcement Comparison for Nylon Thermoplastic

There was a decrease in strength found in both cases with nylon thermoplastic in the change from carbon reinforcement to glass reinforcement (Figure 8-1). The failure

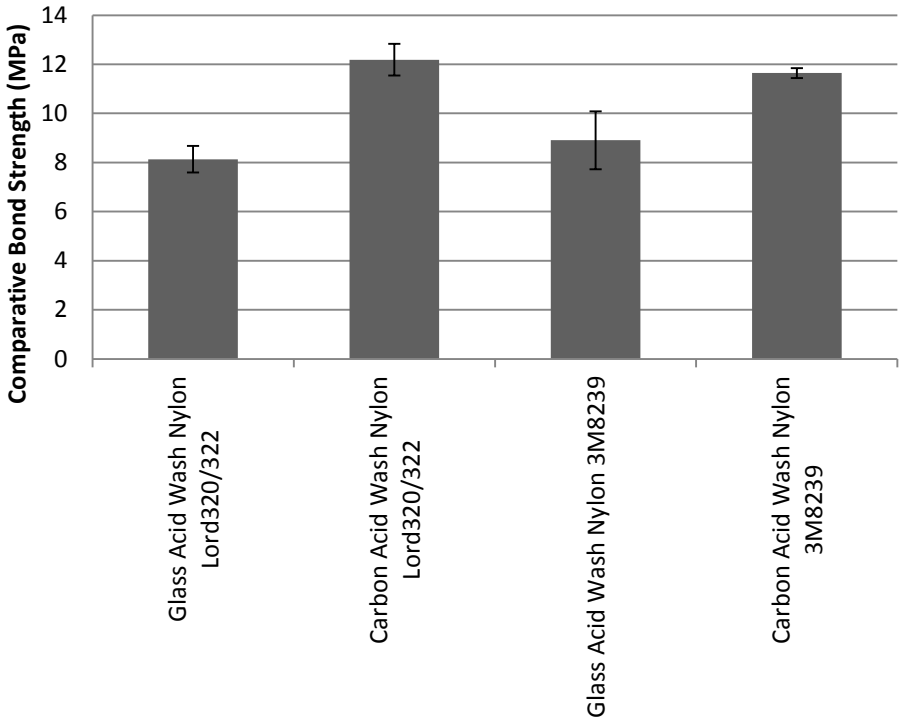

Figure 8-1: Comparative bond strength for nylon glass carbon comparison

modes also changed from a cohesive failure to a fiber matrix interface failure. These results suggest that the nylon thermoplastic does not adhere to the glass reinforcement as well as it adheres to the carbon reinforcement.

The parameter group of acid washed nylon thermoplastic adherends with Lord 320/322 adhesive had an average comparative bond strength of 8.1 MPa (1.2 ksi). The failure mode was primarily fiber/matrix interface failure. The parameter group of acid washed nylon thermoplastic adherends with 3M8239 adhesive had an average comparative bond strength of 8.9 MPa (1.3 ksi). The failure mode was primarily fiber/matrix interface failure.

8.4.2 Carbon to Glass Reinforcement Comparison for Polypropylene Thermoplastic

There was a decrease in strength found in both cases with polypropylene thermoplastic in the change from carbon reinforcement to glass reinforcement (Figure 8-2). The failure modes also changed from a mixed failure with adhesive, cohesive, and fiber/matrix interface failures to a pure fiber/matrix interface failure. These results suggest that the polypropylene thermoplastic does not adhere to the glass reinforcement as well as it adheres to the carbon reinforcement. The parameter group of Openair plasma polypropylene reinforced glass thermoplastic adherends with Dow LESA adhesive with Betaprime primer had an average comparative bond strength of 6.6 MPa (0.96 ksi). The failure mode was primarily fiber/matrix interface failure.

The parameter group of Surface Activation Technologies 482 polypropylene reinforced glass thermoplastic adherends with Dow LESA adhesive with Betaprime primer had an average comparative bond strength of 4.9 MPa (0.71 ksi). The failure mode was primarily fiber/matrix interface failure.

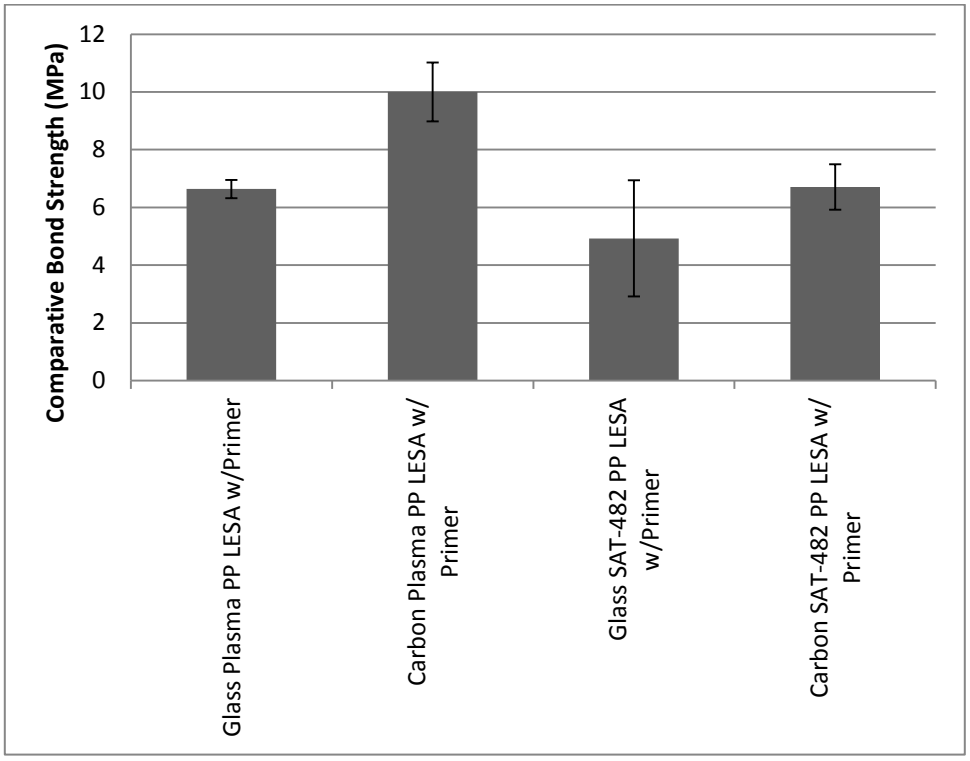

Figure 8-2: Comparative bond strength for polypropylene glass carbon comparison

9 ROUND ONE CONCLUSIONS

The most promising adhesive, surface treatment, and adherend combinations are shown in Table 9-1 for nylon and Table 9-2 for polypropylene. A greater weighting was given to the lap shear strengths than to the fracture toughness.

For nylon, input from the ACC was sought to determine the best selections for follow-on testing. The four combinations shown in bold in Table 9-1 were selected. An adhesive comparison between Lord 320/322 and 3M 8239 could be made across the common surface treatment of acid wash. A surface treatment comparison between acid wash, ATmaP Flame, and Openair Plasma could be made across the common adhesive Lord 320/322.

For polypropylene, input was also sought from the ACC to determine the best selections for follow-on testing. The four combinations shown in bold in Table 9-2 were selected. An adhesive comparison between Lord 320/322, 3M 8239 and Dow LESA with Betamate 5404A could be made across the common surface treatment of Surface Activation Technologies 482. A surface treatment comparison between Openair Plasma and Surface Activation Technologies 482 could be made across the common adhesive Dow LESA with Betamate 5404A primer.

Table 9-1: Selection matrix for nylon candidates in bold for continuation of testing

	Average of Test Results	
	Lap Shear (MPa)	G_{1C} (J/m^2)
Acid Wash Nylon Lord320/322	**12.18**	**834**
Acid Wash Nylon 3M8239	**11.65**	**N/A**
ATmaP Flame Nylon Lord320/322	**11.64**	**852**
Plasma Nylon Lord320/322	**11.33**	**763**
SAT Nylon Lord320/322	10.23	879
Plasma Nylon 3M8239	6.26	1223
Plasma Nylon Bondmaster M1315	2.43	N/A

Table 9-2: Selection matrix for polypropylene candidates in bold for continuation of testing

	Average of Test Results	
	Lap Shear (MPa)	G_{1C} (in-lbs/in^2)
Plasma PP LESA w/ Primer	**10.00**	**2.16**
SAT-481 PP LESA	7.44	0.91
SAT-482 PP LESA w/ Primer	**6.71**	**1.71**
SAT-482 PP Lord 320/322	**6.54**	**2.48**
SAT-482 PP Lord 7542	**6.52**	**2.64**
SAT-483 PP LESA	6.20	2.04
SAT-482 PP LESA	5.09	1.82
ATmaP Flame PP LESA w/ Primer	4.68	N/A
SAT-481 PP LESA w/ Primer	4.57	1.25
Plasma PP LESA	4.31	0.50
SAT-482 PP Lord7542 w/ Zinc Stearate	2.76	N/A
SAT-483 PP LESA w/ Primer	2.55	1.25
SAT-482 PP Lord320/322 w/ Zinc Stearate	2.47	N/A
Plasma PP 3M8239 w/ Zinc Stearate	2.22	N/A
Plasma PP 3M8239	0.91	1.12

10 FLATWISE TENSION

10.1 Introduction

Flatwise tensile testing may be used to assess the as-manufactured performance of the bond between the facesheets and core. A square specimen is adhesively bonded to pin-loaded steel blocks.

The primary functions of this test are to assess the bond strength under an out-of-plane tensile loading and to identify the weakest interface within the sandwich composite. In this investigation, flatwise tensile specimens were tested according to ASTM C 297 [18]. The flatwise tensile strength, failure location, and the failure mode were determined from these tests. This test is also useful for identifying manufacturing related problems such as core crushing, poor adhesive bonding, and improper facesheet consolidation.

10.2 Background

Originally it was envisioned that a larger sandwich panel would be fabricated and the smaller flatwise tension specimens would be cut from this larger sandwich panel. The smaller flatwise tension specimens would then be bonded to the steel fixture blocks. Due to concerns over contamination and fade of the surface treatments on the thermoplastic facesheets, a method for simultaneously bonding the facesheets, core, and fixture blocks was devised, which included a specially manufactured alignment fixture. With both sides of each facesheet having the same surface treatment and the same time amount of time until bonding, the concerns of fade and contamination were minimized. It was also

shown in preliminary testing that the facesheet/fixture block bond was just as susceptible to failure as the facesheet/core bond. With both sides of the facesheet having the same surface treatment and bond time, a failure on either side of the facesheet could be considered possible. Preliminary testing also showed that the strength of the balsa core/facesheet bond was stronger than the facesheet/fixture block bond. However, this was not an issue with the foam core because of the reduced strength of foam as compared to balsa. Therefore, the balsa core was reduced from a 51 mm by 51 mm (2 in x 2 in) cross section to a 38 mm by 38 mm (1.5 in x 1.5 in) cross section which resulted in a 43% reduction in cross sectional area while the facesheets remained full size. This change was intended to eliminate failures at the facesheet/fixture block bond, and try to force the specimen to fail in the core or the facesheet/core interface.

10.3 Methods

Flatwise tension testing specimen geometry was chosen in accordance with ASTM C297 [18]. The specimen facesheets were 4 plies thick and 51 mm (2.0 in) by 51 mm (2.0 in). The dimensions of the foam cores were 51 mm (2.0 in) by 51 mm (2.0 in) and 12.7 mm (0.50 in) thick. The dimensions of the balsa cores were 38 mm (1.5 in) by 38 mm (1.5 in) and 12.2 mm (0.48 in) thick.

The steel fixture blocks were prepared by grit blasting followed by an acetone wipe to remove contaminants. The fixture blocks were masked with duct tape to prevent the adhesive from adhering to the tool. The core was masked with duct tape to prevent the adhesive from adhering to the core and affecting results. Due to the reduction in size for the balsa core, a 1.1 mm (0.04 in) hole was drilled in the center of each facesheet, and an alignment pin was installed. The alignment pin pressed into the reduced balsa core and

prevented its motion during the adhesive bonding process. The alignment fixture was used to check the alignment of the facesheets, reduced balsa core, and fixture blocks, before the inside of the facesheets around the outside of the reduced balsa core were masked with duct tape.

During the bonding process, each surface received an even coating of adhesive, and two spacing wires were placed in each bond line before the surfaces were pressed together. As each piece of the specimen was completed during the bonding process, it was placed in the fixture and alignment was checked at each step. When the specimen had been bonded to the fixture blocks, a steel plate was placed on the specimen and clamped to a solid flat surface with a C-clamp. A C-clamp was used on both ends of the fixture blocks to squeeze the bond lines together. The C-clamp was incrementally tightened to supply sufficient pressure with care being taken to not crush the core. The specimens were left in the fixtures for 24 hours until adequate adhesive strength had been reached for their removal. The tape mask was removed from the tools and core. The excess adhesive was removed with a dremel or a razor blade.

A total of three to six specimens were tested for each test parameter group. Specimens were tested at a constant displacement of 1.3 mm/min (0.05 in/min). The peak load was measured and the flatwise tensile strength was calculated according to ASTM C 297 [18]. Failure mode was also noted for each specimen.

10.4 Results and Discussion

The different parameters that were investigated and the resulting test data are summarized in Table 10-1 and can be viewed graphically in Figure 10-1. Nylon adherends with balsa core were the highest performers. The bond strengths with nylon

were sufficient to produce cohesive failures in the adhesive and core failures in the balsa. In fact the flatwise tension strengths of nylon with balsa were comparable to previous tests on thermoset sandwich composites as seen in Figure 10-1.

The bond strength with polypropylene was not high enough to achieve a failure in the balsa core, but was strong enough to achieve failure in the foam core. The strength of the foam core was not affected by either adherend, nylon or polypropylene, because the bond strengths were strong enough to achieve core failure in every combination.

It was discovered that the 3M 8239 adhesive was incompatible with the balsa core. 3M 8239 is a fast cure with a work time of approximately 1 min. This fast cure time prevents the adhesive from wetting out the balsa core and achieving good mechanical interlocking.

10.5 Summary

The recommended parameter groups from lap shear and cleavage testing were used to produce sandwich panels with two different core materials, balsa and polyurethane foam. These sandwiches were tested in flatwise tensile according to ASTM C 297 [18].

A special method of manufacture was devised to provide better adhesion to the steel fixture blocks. The nylon adherends with the balsa core were the highest scoring group. Adhesion strength with the polypropylene adherends was not sufficient to cause failure in the balsa core but was sufficient to cause failure in the foam core. The adhesive, 3M 8239, was found to be incompatible with the balsa and foam core.

Table 10-1: Flatwise tension results

Sandwich Configuration	Stress (MPa)	Std. Dev. (MPa)	Failure Mode
Openair® Plasma Nylon Lord 320/322 Balsa	7.39	0.92	Core Cohesive
ATmaP® Flame Nylon Lord 320/322 Balsa	5.88	0.50	Core Cohesive
Acid Wash Nylon Lord 320/322 Balsa	5.80	0.57	Core Cohesive
Surface Act Polypro Lord 320/322 Balsa	2.14	0.15	Mixed
Acid Wash Nylon 3M 8239 Balsa	2.11	0.48	Adhesive
ATmaP® Flame Nylon Lord 320/322 Polyurethane Foam	1.82	0.13	Core
Surface Act Polypro Lord 320/322 Foam	1.61	0.10	Core
Openair® Plasma Polypro Dow Lesa w/ Primer Balsa	1.57	0.57	Adhesive
Acid Wash Nylon 3M 8239 Polyurethane Foam	1.54	0.14	Core
Acid Wash Nylon Lord 320/322 Polyurethane Foam	1.54	0.29	Core
Openair® Plasma Nylon Lord 320/322 Polyurethane Foam	1.52	0.12	Core
Surface Act Polypro Lord 7542 Foam	1.49	0.10	Core
Openair® Plasma Polypro Dow Lesa w/ Primer Foam	1.06	0.23	Core
Surface Act Polypro Lord 7542 Balsa	1.02	1.24	Adhesive

Figure 10-1 : Flatwise tension test data

11 CORE SHEAR

11.1 Introduction

Core shear testing may be used to assess the as-manufactured performance of the bond between the facesheets and core. The primary functions of this test are to assess the bond strength under shear loading and to identify the weakest interface within the sandwich composite. In this investigation, core shear specimens were tested according to ASTM C 297 [19]. The core shear strength, failure location, and failure mode were determined. This test is also useful for identifying manufacturing related problems such as core crushing, poor adhesive bonding, and improper facesheet consolidation.

11.2 Background

Originally it was envisioned that a larger sandwich panel would be fabricated and the smaller core shear test specimens would be cut from this larger sandwich panel. The smaller core shear specimens would then be bonded to the steel fixture plates. Due to concerns over contamination of the specially surface treated thermoplastic facesheets, a method for simultaneously bonding the facesheets, core, and fixture plates was devised, which included a specially manufactured alignment fixture. With both sides of each facesheet having the same surface treatment and the same amount of time until bonding, the concerns of fade and contamination were minimized. It was also shown in preliminary testing that the facesheet/fixture plate bond was just as susceptible to failure as the facesheet/core bond. With both sides of the facesheet having the same surface

treatment and bond time, a failure on either side of the facesheet could be possible. Preliminary testing also showed that the strength of the balsa core/facesheet bond was stronger than the facesheet/fixture plate bond. However, this was not an issue with the foam core because of the reduced strength of foam as compared to balsa. Therefore, the balsa core was reduced in length by 12.2 mm (0.5 in) while the facesheets remained the full size. This change was intended to eliminate failures at the facesheet/fixture plate interface, and to try to force the specimen to fail in the core or the facesheet/core interface. The alignment fixture controlled the facesheets and core alignment, while allowing control of the bond line thickness by placing wires within the bond line.

11.3 Methods

Core shear testing specimen geometry was chosen in accordance with ASTM C273 [19]. The manufacturing procedure of the thermoplastic plates outlined in Chapter 3 was followed. An acid wash was performed prior to all surface treatments, in an attempt to remove additional contaminants.

The specimen facesheets were 4 plies thick and 51 mm (2.0 in) wide, and 203 mm (8.0 in) long. The dimensions of the foam cores were 203 mm (8.0 in) long, 51 mm (2.0 in) wide, and 12.7 mm (0.50 in) thick. The dimensions of the balsa cores were 191 mm (7.5 in) long, 51 mm (2.0 in) wide, and 12.2 mm (0.48 in) thick.

The steel fixture plates were prepared by grit blasting followed by an acetone wipe to remove contaminants. The steel fixture plates were masked with duct tape to prevent the adhesive from adhering. The core was masked with duct tape to prevent the adhesive from adhering to the core and affecting results. Due to the reduction in size for the balsa core, the alignment of the facesheet, reduced balsa core, and fixture plates were checked

in the alignment fixture prior to bonding. The inside of the facesheets around the outside of the reduced balsa core was masked with duct tape.

During the bonding process, each surface received an even coating of adhesive, and three spacing wires were placed in each bond line before the surfaces were pressed together. As each piece of the specimen was completed during the bonding process, it was placed in the alignment fixture and alignment was checked at each step. When the specimen had been bonded to the fixture plates, a steel plate was placed on the specimen and clamped to a solid flat surface with a C-clamp. A C-clamp was used on the side of the alignment fixture and on the steel fixture plates to squeeze the bond lines together. The C-clamp was incrementally tightened to supply sufficient pressure with care being taken to not crush the core. The specimens were left in the fixtures for 24 hours until adequate strength had been reached for their removal. The tape mask was removed from the fixture plates and core. The excess adhesive was removed with a dremel or a razor blade.

A total of three to six specimens were tested for each test parameter group. Specimens were tested at a constant displacement rate of 1.3 mm/min (0.05 in/min). The peak load was measured and the core shear strength was calculated according to ASTM C 273 [19]. The failure mode was also noted for each specimen.

11.4 Results and Discussion

The different parameters that were investigated and the resulting data are summarized in Table 11-1 and can be viewed graphically in Figure 11-1. There was no apparent difference between the two different thermoplastic adherends, nylon and polypropylene, in shear as shown in Figure 11-1. The thermoset sandwich composites

Table 11-1: Core shear results

Sandwich Configuration	Average Strength (MPa)	Std. Dev. (MPa)	Failure Mode
Surface Act Polypro Lord 7542 Balsa	1.68	0.07	Core Adhesive
ATmaP® Flame Nylon Lord 320/322 Balsa	1.68	0.29	Cohesive
Openair® Plasma Nylon Lord 320/322 Balsa	1.60	0.14	Core Cohesive
Surface Act Polypro Lord 320/322 Balsa	1.51	0.10	Core Cohesive
Acid Wash Nylon Lord 320/322 Balsa	1.50	0.17	Core Cohesive
Openair® Plasma Polypro Dow Lesa w/ Primer Balsa	1.30	0.22	Mixed
Acid Wash Nylon 3M 8239 Balsa	1.15	0.18	Adhesive
Openair® Plasma Polypro Dow Lesa w/ Primer Foam	0.84	0.08	Core
Surface Act Polypro Lord 7542 Foam	0.79	0.02	Core
Acid Wash Nylon Lord 320/322 Polyurethane Foam	0.76	0.04	Core
ATmaP® Flame Nylon Lord 320/322 Poluyurethane Foam	0.76	0.06	Core
Acid Wash Nylon 3M 8239 Polyurethane Foam	0.73	0.10	Core
Surface Act Polypro Lord 320/322 Foam	0.72	0.07	Core
Openair® Plasma Nylon Lord 320/322 Polyurethane Foam	0.68	0.05	Core

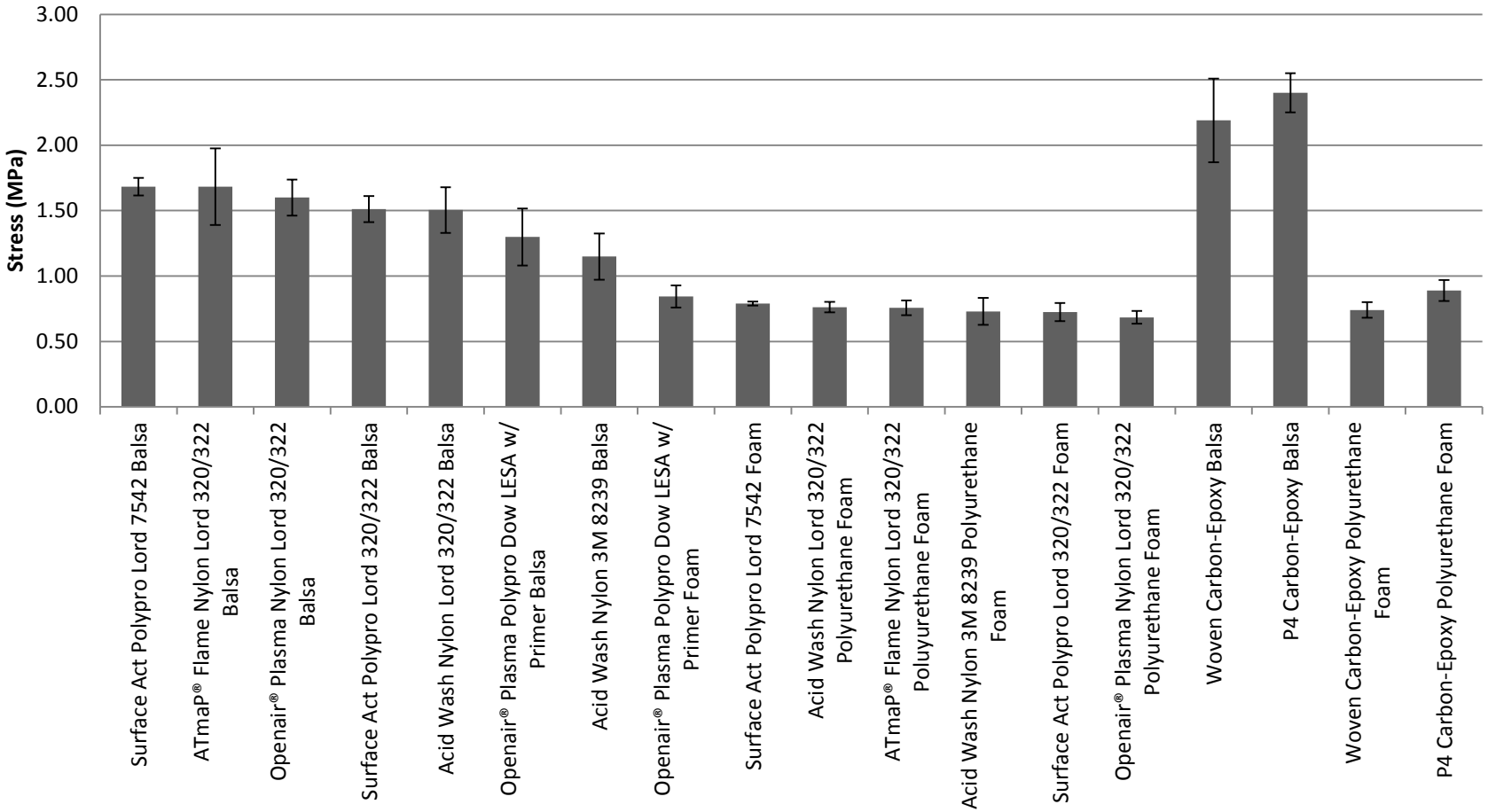

Figure 11-1 : Overall core shear results

made with the balsa core did not perform in a statistically different manner from each other with the exception of the 3M 8239 adhesive. As reported in the flatwise tensile testing, there was an incompatibility between the balsa and the 3M 8239 adhesive. This incompatibility seemed to be less of an issue in shear, but its effects were still apparent. The thermoplastic sandwich composites with the balsa core did not score as high as the previous thermoset sandwich composites.

The thermoplastic sandwich composites with the foam core did not produce statistically significant differences in core shear strengths from each other. The thermoplastic sandwich composites with the foam core scored comparatively with the previous thermoset sandwich composites.

11.5 Summary

The recommended parameter groups from lap shear and cleavage testing were used to produce composite sandwich panels with two different core materials, balsa and polyurethane foam. These composite sandwich configurations were tested using a core shear test configuration according to ASTM C 273 [19].

A special method of manufacture was devised to provide better adhesion to the steel fixture plates. The core shear strength was found to be more dependent on the core than the adherend. The balsa core outperformed the foam core regardless of the adherend, nylon or polypropylene.

12 STATIC EDGEWISE COMPRESSION TESTING

12.1 Introduction

Edgewise compression testing is commonly used to assess the performance of sandwich composites under in-plane compression loading. Although not a direct test of the adhesion of the facesheet to the core, it does provide a good indication of adhesion as well as evaluating failure produced in an end impact.

The primary outputs of this test are the facing compression stress at failure and the failure modes. The energy absorption may be obtained from integrating the area under the load versus displacement curve. In this investigation, edgewise compression specimens were tested according to a modified ASTM C 364 [20].

12.2 Background

According to ASTM C 364 [20], the edgewise specimen should be supported over 13 mm (0.51 in.) of length adjacent to the specimen ends. In this study, the edgewise compression fixture was modified so as to only provide clamping on the bottom 6 mm (0.24 in.) and no clamping on the top of the specimen as shown in Figure 12-1. The top and bottom of the fixture had side clamps with a 45° angled surface. These angled side clamps provided realignment of the specimen in the fixture during crushing. Specimen alignment was maintained using alignment rods and linear bearings in the top portion of

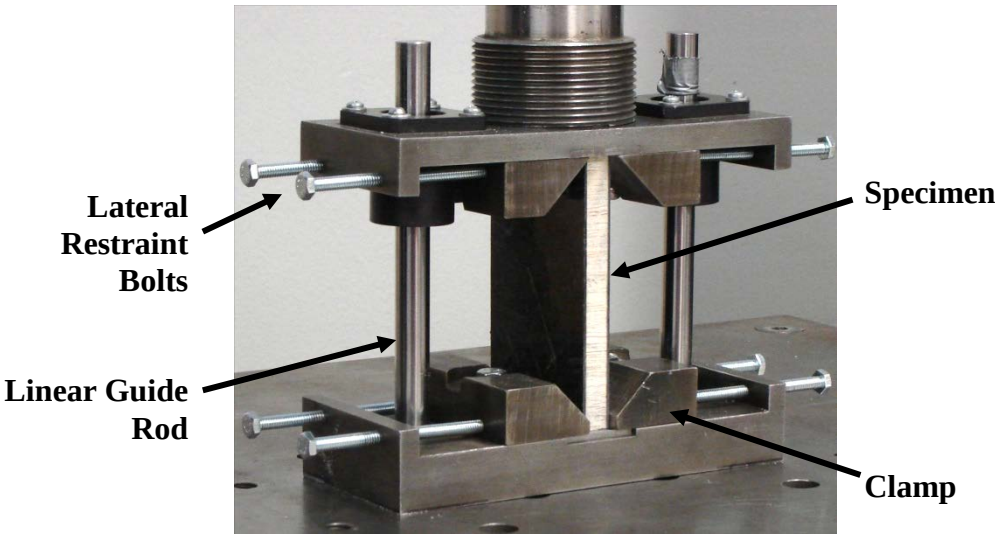

Figure 12-1: Specially designed static edgewise compression testing fixture.

the fixture. Hardened steel contact plates were pressed into the top and bottom specimen contact areas of the fixture to prevent damage due to localized loading. Lateral restraint bolts were also fitted on both the top and bottom clamps to prevent them from spreading during loading.

12.3 Methods

For static edgewise compression testing, the specimen geometry was chosen in accordance with ASTM C 364 [20]. The manufacturing procedure of the thermoplastic plates outlined in Chapter 3 was again followed. An acid wash was performed prior to all surface treatments in an attempt to remove additional contaminants.

Composite sandwich manufacturing went as follows. Facesheets four plies thick and approximately 140 mm by 254 mm (5.5 in by 10 in) were treated with their respective surface treatment. Core material, balsa or foam, was cut to size on a band saw. Bond line thickness wires were bent and pressed into the core material on each end. During the

bonding process, each surface received an even coating of adhesive and alignment was checked before the surfaces were pressed together. The composite sandwich was placed in a die set for 24 hours with additional weights to ensure the proper bondline was achieved. After removal from the die set, the sandwich composite panels were allowed to cure at room temperature for a minimum of 72 hours to ensure a complete and consistent cure before being cut. Each specimen was machined to ensure the loading surfaces were parallel. The final specimen geometry was 76 mm by 127 mm (3.0 in x 5.0 in).

A total of three to six specimens were tested for each test parameter group. The fixture shown in Figure 12-1 was placed under the crosshead. A specimen was placed between the V-block clamps, and the lateral restraint bolts were tightened to hold the specimen in place. Specimens were tested at a constant displacement rate of 7.6 mm/min (0.3 in/min) for a distance of 50.8 mm (2.0 in). The peak load was measured as well as the load versus displacement recorded. The peak load was used to calculate the edgewise compression strength of the panel, and the load versus displacement curve was integrated to find the total energy absorbed.

12.4 Results and Discussion

12.4.1 Static Average Edgewise Compression Strength

The different composite sandwich panels were tested and the average edgewise compression strength was computed and summarized in Tables 12-1 and 12-2 and can be viewed graphically in Figure 12-2.

The nylon facesheet sandwich composites had a higher average edgewise compression strength over the polypropylene facesheet sandwich composites. This result

Table 12-1: Static nylon edgewise compression strengths

Sandwich Configuration	Max Load (kN)	Ult. Strength (MPa)	Initial Failure Mode	Average Ult. Strength (MPa)	Std. Deviation (MPa)
Openair Plasma Nylon Lord 320/322 Balsa	52	266	Facesheet Buckling	265	11
	49	249	End Crushing		
	54	275	Facesheet Buckling		
	53	271	End Crushing		
	54	276	End Crushing		
	50	255	Facesheet Buckling		
Acid Wash Nylon Lord 320/322 Balsa	48	251	End Crushing	255	21
	49	251	End Crushing		
	56	288	Facesheet Buckling		
	44	224	End Crushing		
	50	259	Facesheet Buckling		
	50	256	Facesheet Buckling		
ATmaP Flame Nylon Lord 320/322 Foam	46	236	Facesheet Buckling	235	8
	44	227	Facesheet Buckling		
	43	223	Facesheet Buckling		
	48	247	Facesheet Buckling		
	46	237	Facesheet Buckling		
	46	237	Facesheet Buckling		
Openair Plasma Nylon Lord 320/322 Foam	43	224	Facesheet Buckling	219	8
	43	220	Facesheet Buckling		
	41	210	Facesheet Buckling		
	45	231	Facesheet Buckling		
	42	217	Facesheet Buckling		
	41	212	Facesheet Buckling		
Acid Wash Nylon Lord 320/322 Foam	40	208	Facesheet Buckling	204	14
	40	204	Facesheet Buckling		
	39	201	Facesheet Buckling		
	42	215	Facesheet Buckling		
	42	217	Facesheet Buckling		
	35	178	Facesheet Buckling		

Table 12-2: Static polypropylene edgewise compression strengths

Sandwich Configuration	Max Load (kN)	Ult. Strength (MPa)	Initial Failure Mode	Average Ult. Strength (MPa)	Std. Deviation (MPa)
Openair Plasma Polypro Dow LESA w/Primer Foam	25	128	End Crushing	118	24
	17	89	General Buckling		
	24	123	General Buckling		
	29	151	End Crushing		
	24	125	End Crushing		
	18	92	End Crushing		
Openair Plasma Polypro LESA w/Primer Balsa	24	122	Facesheet Buckling	129	12
	27	136	End Crushing		
	26	137	General Buckling		
	23	120	End Crushing		
	28	145	Facesheet Buckling		
	22	114	End Crushing		
Surface Activation Polypro Lord 320/322 Foam	29	147	End Crushing	148	9
	27	140	End Crushing		
	31	157	General Buckling		
Surface Activation Polypro Lord 320/322 Balsa	26	134	Facesheet Buckling	150	17
	29	148	Facesheet Buckling		
	33	169	Facesheet Buckling		
Surface Activation Polypro Lord 7542 Foam	25	126	End Crushing	114	21
	17	90	General Buckling		
	24	125	General Buckling		
Surface Activation Polypro Lord 7542 Balsa	23	118	End Crushing	116	2
	22	114	End Crushing		
	23	117	Facesheet Buckling		

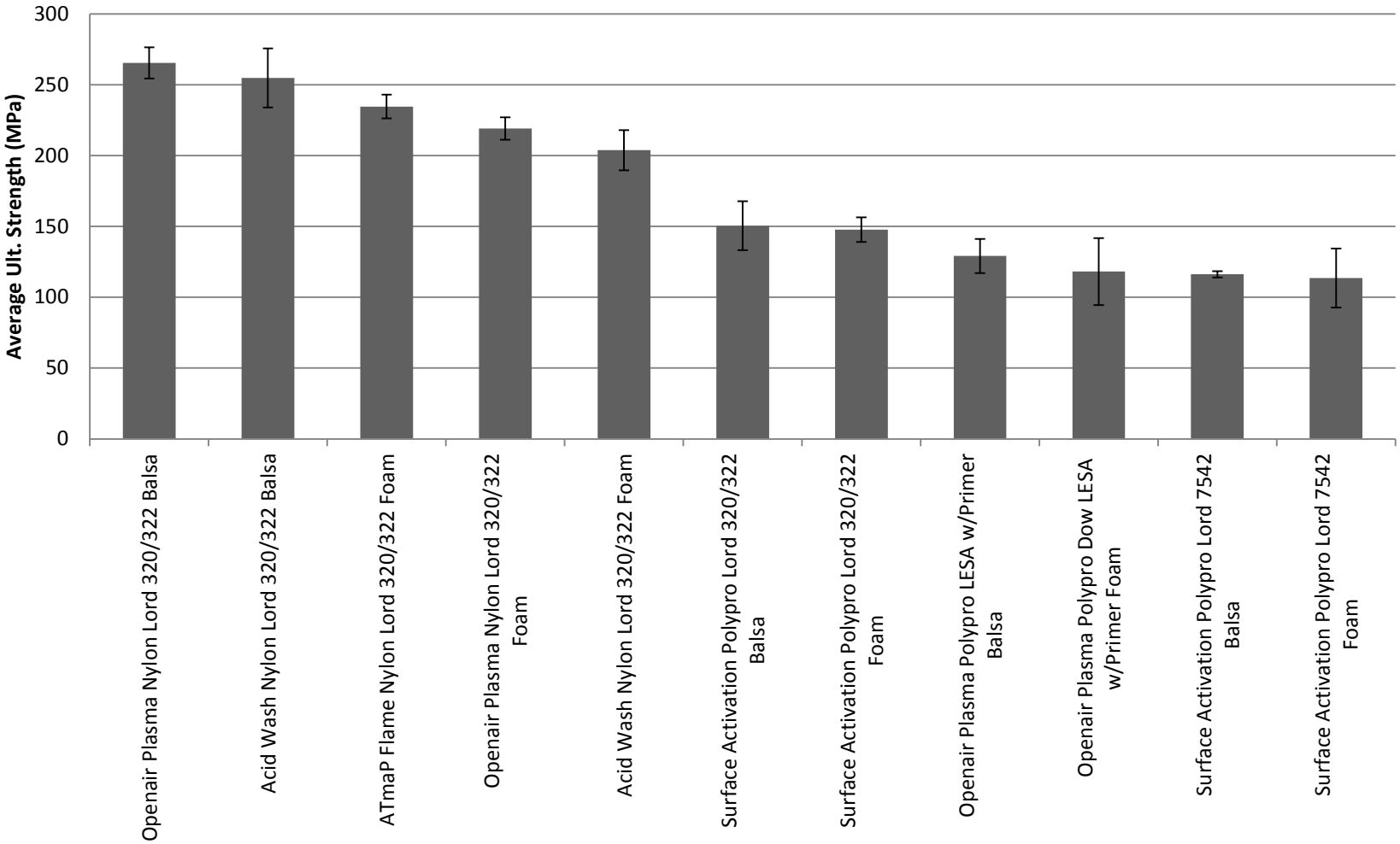

Figure 12-2: Static edgewise compression strengths

was expected, since nylon produced a stronger, stiffer facesheet and the edgewise compression strength of the sandwich composite is produced mainly by the facesheets. This result is further evidenced by the fact that nylon facesheets with foam outperformed the polypropylene with the balsa core. Although the edgewise compression strength of the sandwich is mainly produced by the facesheets, the bond between the core and the facesheets also contribute to the overall strength of the sandwich. This is evidenced by the fact that nylon facesheets with the balsa core outperformed the nylon facesheets with the foam core.

The polypropylene facesheet sandwich composites had a lower average edgewise compression strength than the nylon facesheet sandwich composites. This result was believed to be a result of the polypropylene facesheet being weaker and less stiff than the nylon facesheets. There was no difference in edgewise compression strength between the two cores with polypropylene facesheets. This result can be attributed to a weaker bond strength between the core and the facesheet. The foam core with the polypropylene facesheets mainly had failures in the foam core where the balsa core with the polypropylene facesheets mainly had adhesive failures.

12.4.2 Static Energy Absorption

The average energy absorption was computed and summarized in Tables 12-3 and 12-4 and can be viewed graphically in Figure 12-3. Nylon facesheets with the balsa core had the highest energy absorption of all the candidates. The strength of the bond that can be achieved with the nylon facesheet and the crack arrest properties of the balsa core allowed for more reloading and a higher absorption of energy over the other candidate sandwich configurations. Conversely, nylon facesheets with the foam core had the

Table 12-3: Static nylon edgewise comprssion absorbed energy

Sandwich Configuration	Energy (N m)	Average Energy (N m)	Std Dev (N m)
Openair Plasma Nylon Lord 320/322 Balsa	297.45	546.01	223.95
	510.19		
	520.95		
	932.00		
	640.31		
	375.16		
Acid Wash Nylon Lord 320/322 Balsa	624.90	419.42	140.21
	510.85		
	301.14		
	469.57		
	355.21		
	254.84		
ATmaP Flame Nylon Lord 320/322 Foam	139.75	122.81	28.81
	131.22		
	167.79		
	96.78		
	108.04		
	93.25		
Openair Plasma Nylon Lord 320/322 Foam	168.71	157.60	14.04
	141.02		
	140.68		
	172.85		
	156.53		
	165.81		
Acid Wash Nylon Lord 320/322 Foam	97.16	149.11	33.95
	185.67		
	153.33		
	127.10		
	147.30		
	184.09		

Table 12-4: Static polypropylene edgewise compression absorbed energy

Sandwich Configuration	Energy (N m)	Average Energy (N m)	Std Dev (N m)
Openair Plasma Polypro Dow LESA w/Primer Foam	386.52	291.68	91.52
	160.62		
	240.75		
	272.64		
	404.40		
	285.14		
Openair Plasma Polypro LESA w/Primer Balsa	270.43	335.42	67.21
	446.73		
	271.30		
	363.75		
	307.77		
	352.57		
Surface Activation Polypro Lord 320/322 Foam	246.95	212.26	30.44
	190.03		
	199.79		
Surface Activation Polypro Lord 320/322 Balsa	327.01	394.27	152.86
	569.22		
	286.58		
Surface Activation Polypro Lord 7542 Foam	262.16	182.89	68.81
	147.99		
	138.53		
Surface Activation Polypro Lord 7542 Balsa	288.15	341.39	105.71
	463.14		
	272.89		

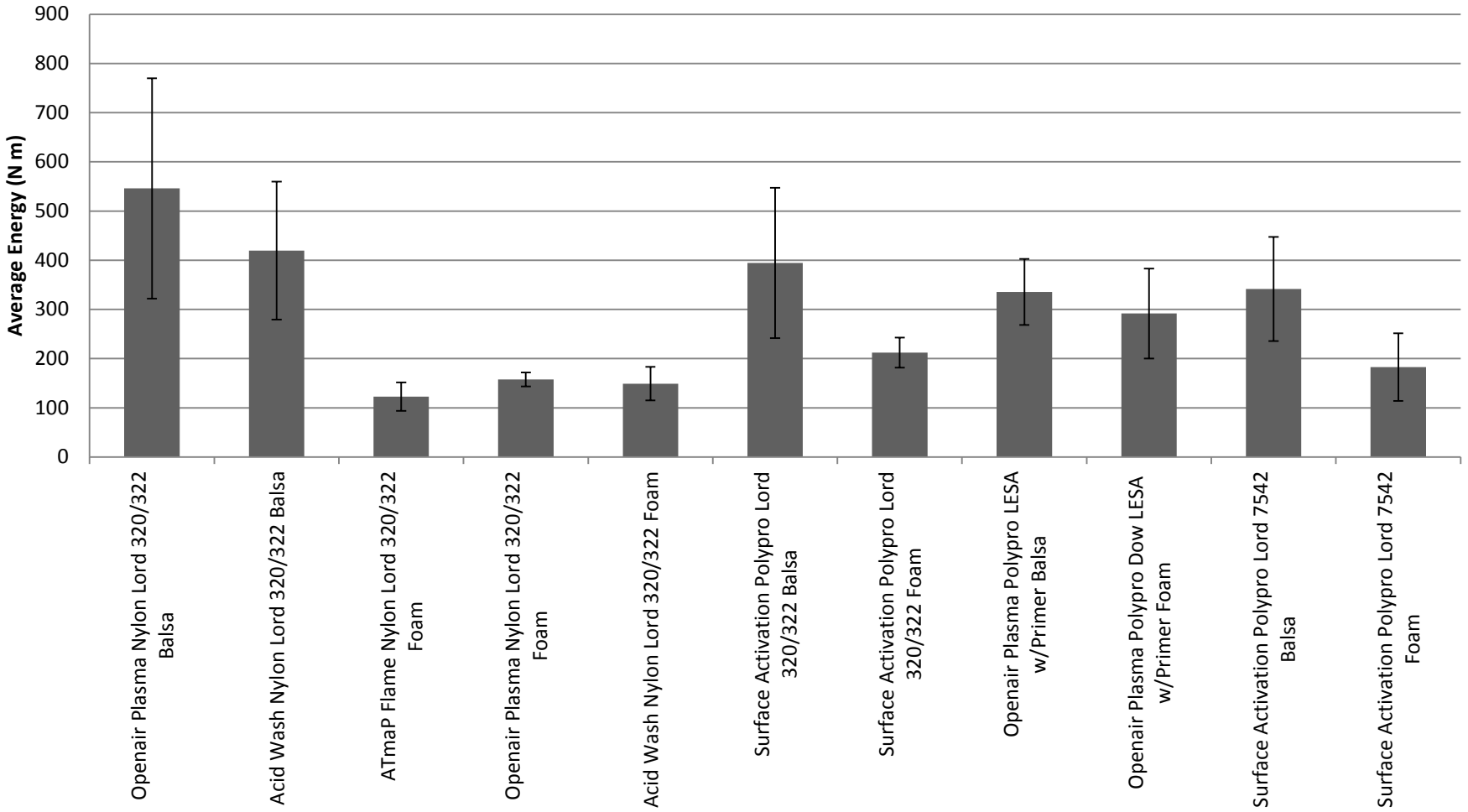

Figure 12-3 : Static edgewise compression absorbed energy

lowest energy absorption of all the configurations. The higher stiffness and strength of the nylon facesheets led to a catastrophic failure of the sandwich composite. The facesheets completely detached from the core, no longer allowing the core/facesheet interaction. After the facesheets were detached from the core, energy could only be absorbed by the buckling of the nylon facesheets.

Polypropylene facesheets with the balsa core were the second highest absorber of energy. The crack resistance of the balsa core and the polypropylene facesheets contributed to the higher level of energy absorption. Polypropylene facesheets with the foam core outperformed nylon facesheets with the foam core. The compliance of the polypropylene facesheets allowed for more crushing while remaining attached to the foam core, resulting in higher energy absorption.

12.4.3 Static Average Weight-Normalized Edgewise Compression Strength

The average ultimate strength was normalized by weight and summarized in Tables 12-5 and 12-6 and can be viewed graphically in Figure 12-4.

When the static average edgewise compression strength data are normalized by weight, the same general trend can be seen, as with the non-normalized data. However, the differences between the balsa core and the foam core sandwiches were greater due to the greater mass per volume of the foam core as compared to the balsa core.

The nylon facesheet sandwich composites had a higher average weight- normalized edgewise compression strength than the polypropylene facesheet sandwich composites. The nylon facesheets with the foam core outperformed the polypropylene with the balsa core even while normalized for weight. Although the load applied to the sandwich

Table 12-5: Static nylon weight-normalized edgewise compression strengths

Sandwich Configuration	Weight (g)	Length (mm)	Width (mm)	Ult Strength per Areal Weight (MPa/kg/m²)	Average Ult Strength per Areal Weight (MPa/kg/m²)	Std. Deviation per Areal Weight (MPa/kg/m²)
Openair Plasma Nylon Lord 320/322 Balsa	70.07	127.15	76.50	36.97	35.27	1.53
	72.62	126.92	76.71	33.38		
	72.40	126.85	76.68	36.93		
	75.28	126.87	76.91	35.09		
	75.88	127.05	76.94	35.56		
	73.77	126.92	76.81	33.71		
Acid Wash Nylon Lord 320/322 Balsa	76.76	126.37	75.69	31.30	31.58	2.10
	78.61	126.75	76.38	30.92		
	80.02	126.87	76.48	34.98		
	76.74	126.75	77.06	28.46		
	79.30	126.87	76.73	31.76		
	77.52	126.80	76.71	32.06		
ATmaP Flame Nylon Lord 320/322 Foam	80.30	126.92	76.48	28.52	29.18	1.45
	78.87	126.95	76.53	28.02		
	79.27	126.75	76.30	27.22		
	78.34	127.18	76.45	30.70		
	75.45	127.08	76.35	30.50		
	76.20	126.97	76.40	30.11		
Openair Plasma Nylon Lord 320/322 Foam	81.35	126.92	76.28	26.64	26.79	1.11
	80.19	126.95	76.48	26.68		
	80.90	126.75	76.43	25.14		
	78.67	127.18	76.38	28.57		
	77.75	127.08	76.71	27.21		
	77.55	126.97	76.43	26.52		
Acid Wash Nylon Lord 320/322 Foam	81.17	127.03	76.58	24.91	24.28	1.69
	80.23	126.64	76.43	24.61		
	82.22	126.57	76.50	23.62		
	80.79	126.59	76.73	25.83		
	82.60	126.47	76.61	25.51		
	81.17	126.26	76.63	21.21		

Table 12-6: Static polypropylene weight-normalized edgewise compression strengths

Sandwich Configuration	Weight (g)	Length (mm)	Width (mm)	Ult Strength per Areal Weight (MPa/kg/m²)	Average Ult Strength per Areal Weight (MPa/kg/m²)	Std. Deviation per Areal Weight (MPa/kg/m²)
Openair Plasma Polypro Dow LESA w/Primer Foam	83.40	126.70	76.58	14.93	13.89	2.14
	76.54	126.62	76.48	11.30		
	83.94	126.70	76.50	14.18		
	85.86	126.72	76.12	17.00		
	83.79	126.49	76.07	14.34		
	76.71	126.75	76.40	11.61		
Openair Plasma Polypro LESA w/Primer Balsa	62.70	127.23	76.17	18.79	20.38	1.33
	60.22	126.26	76.58	21.90		
	63.58	125.73	76.12	20.62		
	58.59	126.01	76.30	19.68		
	63.46	125.70	76.17	21.93		
	57.00	126.29	76.38	19.36		
Surface Activation Polypro Lord 320/322 Foam	90.92	125.48	76.86	15.55	15.65	0.14
	87.02	126.80	76.61	15.58		
	97.09	127.00	77.09	15.81		
Surface Activation Polypro Lord 320/322 Balsa	76.72	125.63	76.94	16.94	19.53	2.37
	71.92	126.52	77.14	20.09		
	76.28	126.52	77.06	21.57		
Surface Activation Polypro Lord 7542 Foam	84.37	126.64	77.01	14.56	13.07	2.44
	85.43	127.43	76.84	10.26		
	85.18	127.25	76.94	14.40		
Surface Activation Polypro Lord 7542 Balsa	78.70	127.33	77.17	14.76	13.97	0.69
	82.88	126.85	77.34	13.48		
	83.36	126.52	77.32	13.67		

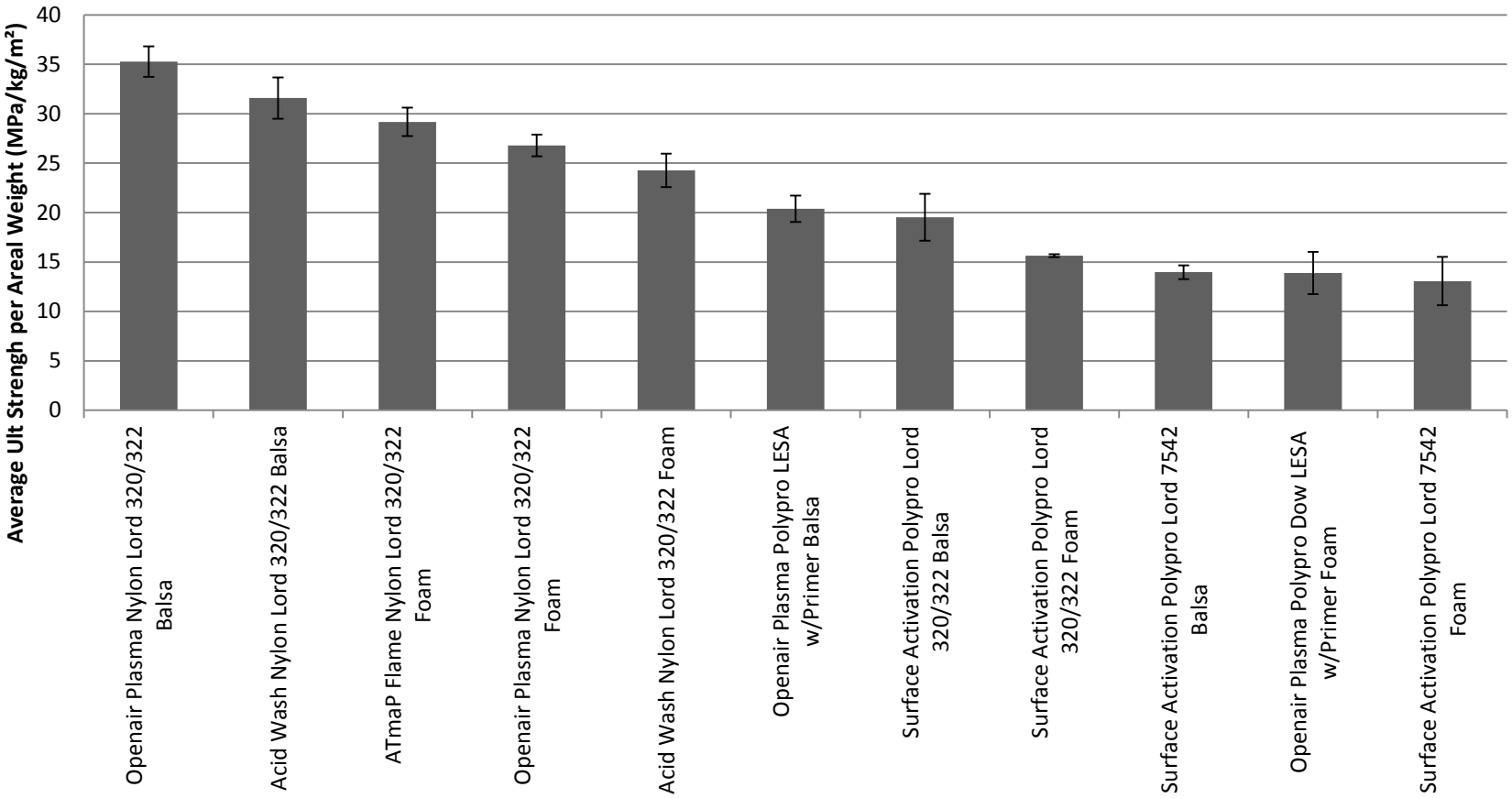

Figure 12-4 : Static weight-normalized edgewise compression strengths

composite is mainly carried by the facesheets, the interaction between the core and the facesheets also contribute to the overall strength of the sandwich composite. Nylon facesheets with balsa core outperformed the nylon facesheets with the foam core.

Polypropylene facesheet sandwich composites had a lower average weight-normalized edgewise compression strength than nylon. The a difference in the weight-normalized strength of the different cores, balsa or foam, become evident with the polypropylene facesheets. This difference is attributed to the greater mass per volume of the foam core, resulting in a lower weight-normalized ultimate strength.

12.4.4 Static Weight-Normalized Energy Absorption

The average energy absorption was normalized by weight and summarized in Tables 12-7 and 12-8 and can be viewed graphically in Figure 12-5.

When the average energy absorption data are normalized by weight, the same general trend can be seen as with the non-weight-normalized data. However, the differences between the balsa core and the foam core sandwich composites were greater due to the greater mass per volume of the foam core as compared to the balsa core.

Nylon facesheets with the balsa core had the highest weight-normalized energy absorption of all the sandwich configurations. The strength of the bond that can be achieved with the nylon facesheet and the crack arrest properties of the balsa coreallowed for more reloading and a higher absorption of energy over the other configurations. Conversely, the nylon facesheets with the foam core had the lowest energy absorption of all the configurations. The nylon facesheets produced a catastrophic failure of the

Table 12-7: Static nylon weight-normalized edgewise compression absorbed energy

Sandwich Configuration	Weight (g)	Length (mm)	Width (mm)	Energy per Areal Weight (N m / kg/m²)	Average Energy per Areal Weight (N m / kg/m²)	Std. Dev. (N m / kg/m²)
Openair Plasma Nylon Lord 320/322 Balsa	70.07	127.15	76.50	41.30	72.09	28.12
	72.62	126.92	76.71	68.40		
	72.40	126.85	76.68	69.99		
	75.28	126.87	76.91	120.81		
	75.88	127.05	76.94	82.49		
	73.77	126.92	76.81	49.58		
Acid Wash Nylon Lord 320/322 Balsa	76.76	126.37	75.69	77.87	52.11	17.66
	78.61	126.75	76.38	62.91		
	80.02	126.87	76.48	36.51		
	76.74	126.75	77.06	59.77		
	79.30	126.87	76.73	43.61		
	77.52	126.80	76.71	31.98		
ATmaP Flame Nylon Lord 320/322 Foam	80.30	126.92	76.48	16.89	15.22	3.30
	78.87	126.95	76.53	16.17		
	79.27	126.75	76.30	20.47		
	78.34	127.18	76.45	12.01		
	75.45	127.08	76.35	13.89		
	76.20	126.97	76.40	11.87		
Openair Plasma Nylon Lord 320/322 Foam	81.35	126.92	76.28	20.08	19.29	1.90
	80.19	126.95	76.48	17.07		
	80.90	126.75	76.43	16.84		
	78.67	127.18	76.38	21.34		
	77.75	127.08	76.71	19.62		
	77.55	126.97	76.43	20.75		
Acid Wash Nylon Lord 320/322 Foam	81.17	127.03	76.58	11.64	17.77	4.07
	80.23	126.64	76.43	22.40		
	82.22	126.57	76.50	18.06		
	80.79	126.59	76.73	15.28		
	82.60	126.47	76.61	17.28		
	81.17	126.26	76.63	21.94		

Table 12-8: Static polypropylene weight-normalized edgewise compression absorbed energy

Sandwich Configuration	Weight (g)	Length (mm)	Width (mm)	Energy per Areal Weight (N m / kg/m²)	Average Energy per Areal Weight (N m / kg/m²)	Std. Dev. (N m / kg/m²)
Openair Plasma Polypro Dow LESA w/Primer Foam	83.40	126.70	76.58	44.97	34.36	10.15
	76.54	126.62	76.48	20.32		
	83.94	126.70	76.50	27.80		
	85.86	126.72	76.12	30.63		
	83.79	126.49	76.07	46.44		
	76.71	126.75	76.40	35.99		
Openair Plasma Polypro LESA w/Primer Balsa	62.70	127.23	76.17	41.80	53.36	12.29
	60.22	126.26	76.58	71.73		
	63.58	125.73	76.12	40.84		
	58.59	126.01	76.30	59.69		
	63.46	125.70	76.17	46.44		
	57.00	126.29	76.38	59.66		
Surface Activation Polypro Lord 320/322 Foam	90.92	125.48	76.86	26.20	22.52	3.23
	87.02	126.80	76.61	21.21		
	97.09	127.00	77.09	20.15		
Surface Activation Polypro Lord 320/322 Balsa	76.72	125.63	76.94	41.20	51.69	22.25
	71.92	126.52	77.14	77.25		
	76.28	126.52	77.06	36.63		
Surface Activation Polypro Lord 7542 Foam	84.37	126.64	77.01	30.31	21.06	8.02
	85.43	127.43	76.84	16.96		
	85.18	127.25	76.94	15.92		
Surface Activation Polypro Lord 7542 Balsa	78.70	127.33	77.17	35.98	40.94	12.18
	82.88	126.85	77.34	54.82		
	83.36	126.52	77.32	32.02		

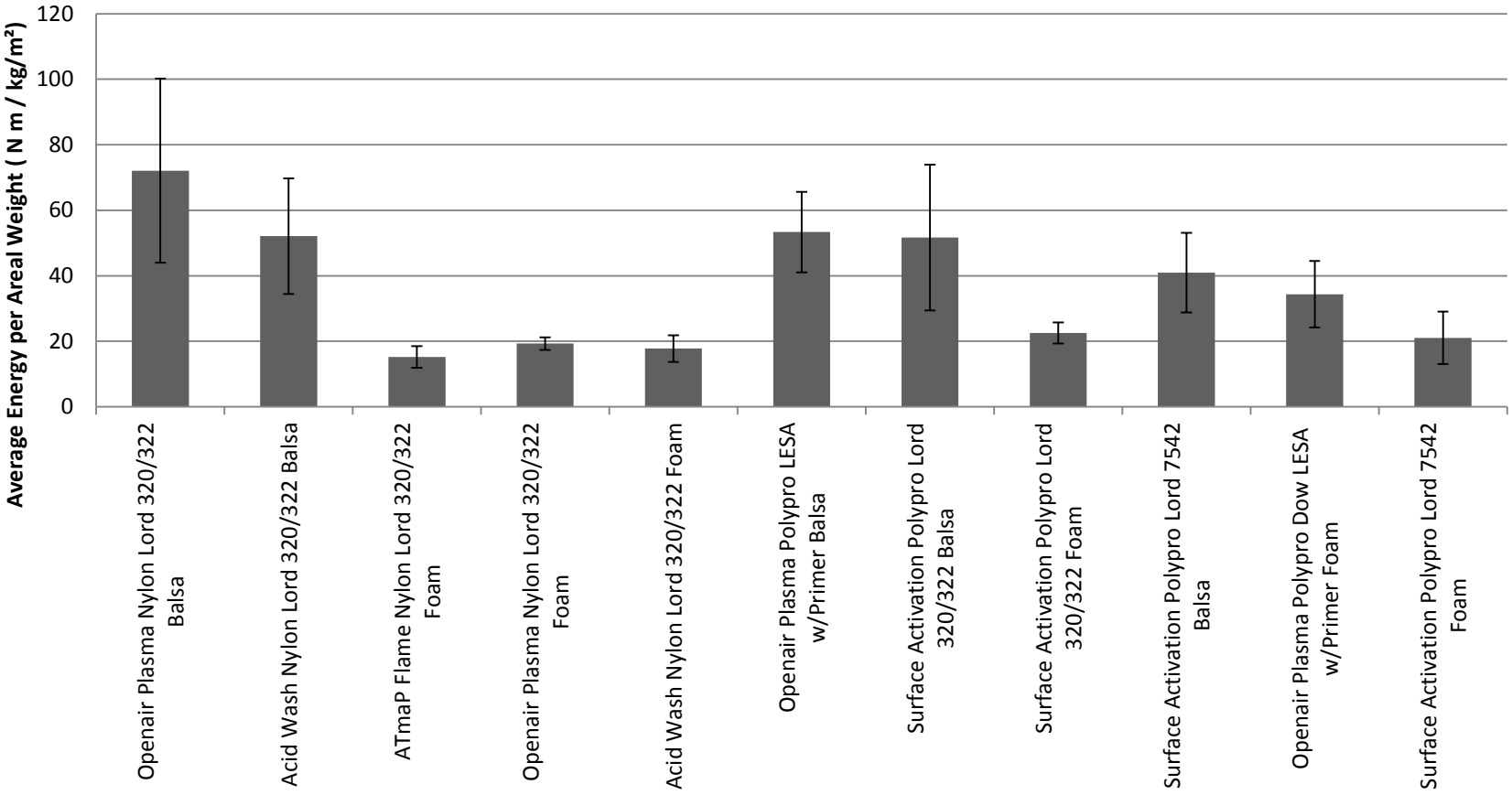

Figure 12-5 : Static weight-normalized edgewise compressive absorbed energy

sandwich composite where the facesheets completely detached from the core, no longer allowing the core facesheet interaction. After the facesheets were detached from the core, no further crushing can occur and all the energy absorbed was from the buckling of the facesheets instead of the crushing of the facesheet and core.

Polypropylene facesheets with the balsa core were the second highest absorber of energy. The crack resistance of balsa wood and the polypropylene facesheets contributed to the level of energy absorption. Polypropylene facesheets with the foam core outperformed nylon facesheets with the foam core. The compliance of the polypropylene facesheets allowed for more crushing while remaining attached to the foam core resulting in higher energy absorption.

12.5 Summary

The parameter groups that showed the most promise from flatwise and core shear testing were used to produce sandwich panels with two different core materials, balsa and polyurethane foam. These sandwich configurations were tested in edgewise compression modified from ASTM C 364.

In general, nylon produced higher edgewise compression strengths than polypropylene. Balsa wood core sandwich configurations absorbed more energy than foam core sandwich configurations. Polypropylene with foam core absorbed more energy than nylon with foam core. Failure mode and absorbed energy were reported for individual specimens tested from each sandwich configuration.

13 DYNAMIC EDGEWISE COMPRESSION

13.1 Introduction

Dynamic edgewise compression testing is used to determine the facing compression stress at failure under dynamic loading conditions. Additionally, the energy absorption may be obtained from integrating the area under the load versus displacement curve. In this investigation, dynamic edgewise compression specimens were tested according to a modified ASTM C 364 [20] procedure.

13.2 Methods

For dynamic edgewise compression testing, the specimen geometry was chosen in accordance with ASTM C 364 [20]. The procedure for manufacturing of the thermoplastic plates outlined in Chapter 3 was again followed. An acid wash was performed prior to all surface treatments in an attempt to remove additional contaminants.

To manufacture the composite sandwich panels, the four-ply thick facesheets, approximately 140 mm by 254 mm (5.5 in by 10 in) were treated with their respective surface treatment. The core material, either balsa or foam, was cut to size on a band saw. Bond line thickness wires were bent and pressed into the core material on each end. During the bonding process, each surface received an even coating of adhesive and alignment was checked before the surfaces were pressed together. The composite sandwich was placed in a die set for 24 hours with additional weights to ensure the proper

bondline thickness was achieved. After removal from the die set, the sandwich composite panels were allowed to cure at room temperature for a minimum of 72 hours to ensure a complete and consistent cure before being cut. Each specimen was machined to ensure the loading surfaces were parallel. The final specimen geometry was 76 mm by 127 mm (3.0 in x 5.0 in).

Drop weight testing was used to assess the edgewise compression performance of the sandwich configurations under dynamic loading. The test configuration used for edgewise drop-weight impact testing is shown in Figure 13.1. The test fixture used was modeled after the fixture used in static edgewise compression testing, but was adapted to the drop-weight tower. The crosshead of the impact tower had a mass of 40.6 kg (89.5 lbs) and the fixture above the force link had a mass of 10.0 kg (22.0 kg). Damping springs and metal stoppers were used to prevent the top fixture from colliding with the bottom fixture.

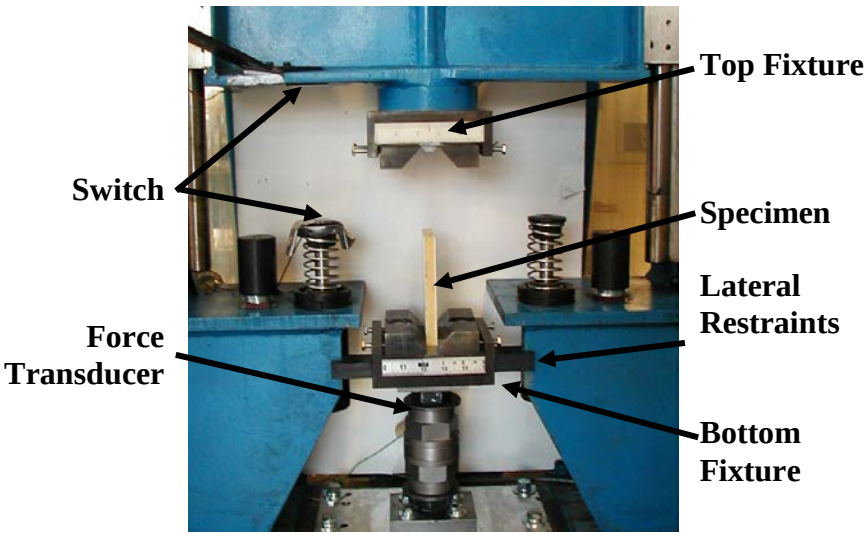

Figure 13-1: Specially designed dynamic edgewise compression testing setup.

A switch was located on the damping springs to signal the end of the specimen crush length so that the springs and stoppers would not be included in the impact. A drop height of 2.1 m (7 ft.) was selected, producing an initial crosshead velocity of 5.8 m/s (19.0 ft/s).

The energy absorption, peak load, and facing stress were determined for each sandwich specimen tested. Energy absorption was recorded over a 51 mm crush length controlled by the damping spring switch. The force versus time data were recorded by a Kistler 9372A quartz force link attached between the lower fixture and the tower base. The charge output of the force link was converted into a proportionally controlled voltage using a Kistler 5010B charge amplifier. Data were collected at a sampling rate of 50 kHz using National Instruments LabVIEW 7.1 with no filtering. The force versus time data were numerically integrated to obtain the force versus displacement data. The force versus displacement data were numerically integrated to obtain the total energy absorption.

13.3 Derivation of Dynamic Energy Absorption Method

The derivation of dynamic energy absorption method uses energy balances to solve for the unknown velocities, allowing the numerical integration of the force versus time curve to a force versus displacement.

The potential energy of the system at time zero is

$$U_p = M_c g h_c + M_f g h_f \tag{13.1}$$

where,

U_p = the potential energy of the system (N-m)

M_c = the mass of the crosshead (kg)

M_f = the mass of the lower fixture (kg)

g = the acceleration due to gravity (m/s^2)

h_c = the height of the crosshead above the lower fixture (m)

h_f = the height of the lower fixture (m)

At the time immediately before impact and neglecting friction, it is assumed that all potential energy is converted to kinetic energy given by

$$M_c g h_c + M_f g h_f = \frac{1}{2} M_c v_c^2 + \frac{1}{2} M_f v_f^2 \quad , \tag{13.2}$$

where,

v_c = the velocity of the crosshead at right before of impact (m/s)

v_f = the velocity of the lower fixture during impact (m/s)

The velocity and height of the lower fixture immediately before of impact is 0. The velocity at the time of impact of the crosshead can be solved using

$$v_c = \sqrt{2gh_c} \tag{13.3}$$

The result given in Equation 13.3 is to be expected as there are no other forms of energy to contribute to the velocity of the crosshead.

While the crosshead is providing all the potential energy, and the motion of the lower fixture is essentially zero, the mass of the lower fixture must still be accelerated over its infinitesimal distance to impart a force on the force washer. Therefore, at the time of impact it is assumed that the mass of the crosshead and the mass of the lower fixture combine into one system:

$$M_s = M_c + M_f \tag{13.4}$$

with a mass equal to the sum of the crosshead and the lower fixture. It is also assumed that all kinetic energy from immediately before impact is imparted on this new system. By using an energy balance and combining Equations 13.3 and 13.4, we get

$$\frac{1}{2} M_c \left(\sqrt{2gh_c}\right)^2 = \frac{1}{2} M_s v_0^2 \tag{13.5}$$

where,

v_0 = velocity of the system at time zero (m/s).

The velocity of the system can now be solved for and is given by

$$v_0 = \left(\frac{2M_c g h_c}{M_s} \right)^{1/2} \tag{13.6}$$

The instantaneous acceleration of the crosshead can be found using the force output data from the force washer using

$$a_n = \frac{-F_n}{M_s} \tag{13.7}$$

The instantaneous velocity of the crosshead can be found by numerically integrating acceleration with respect to time, and adding that to the instantaneous velocity at the earlier integration using Equation 13.7 with the first unknown constant of integration given by Equation 13.7,

$$v_n = v_{n-1} + \frac{a_n + a_{n+1}}{2}(t_{n+1} - t_n) \quad . \tag{13.8}$$

The same numerical techniques can be used to find the deflection of the specimen. Using Equation 13.9 with the first unknown constant of integration being equal to 0,

$$d_n = d_{n-1} + \frac{v_n + v_{n+1}}{2}(t_{n+1} - t_n) \quad . \tag{13.9}$$

Finally, the energy absorbed by the specimen can be found by summing up the integral of the force and deflection plot using Equation 13.10,

$$U_a = \sum_{i=1}^{N}\left[(d_{i+1} - d_i)\frac{F_{i+1} + F_i}{2}\right] \tag{13.10}$$

Verification of this derivation is achieved when there is insufficient potential energy to achieve a full crush of the specimen. A specimen that does not fully crush would absorb a little less than the full amount of energy available, with the difference in absorbed energy going into friction and crosshead "bounce." All specimens that did not fully crush were determined to absorb 15% less than the total amount of energy available.

13.4 Results and Discussion

13.4.1 Dynamic Average Edgewise Compression Strength

The different sandwich panels were tested and the average ultimate strength was computed and summarized in Tables 13-1 and 13-2 and can be viewed graphically in Figure 13-2.

Nylon facesheet sandwich composites with the balsa core had the highest average dynamic ultimate strength in testing as shown in Figure 13-2. Nylon facesheet sandwich composites with the foam core had the second highest average dynamic edgewise compression strength in testing as shown in Figure 13-2.

Polypropylene facesheet sandwich composites had a lower average dynamic ultimate strength than sandwich composites with nylon facesheets. The difference in strengths between the balsa and foam cores were not as evident with the polypropylene facesheets.

Table 13-1: Dynamic nylon edgewise compression strengths

Sandwich Configuration	Max Load (kN)	Ult. Strength (MPa)	Average Ult. Strength (MPa)	Std. Deviation (MPa)
Openair Plasma Nylon Lord 320/322 Balsa	83.17	427.41	459.09	55.74
	101.24	520.80		
	96.75	497.56		
	97.92	503.42		
	74.46	381.29		
	82.60	424.06		
Atmap Flame Nylon Lord 320/322 Foam	67.47	348.25	311.54	49.32
	49.63	255.48		
	n/a	n/a		
	64.19	330.89		
	n/a	n/a		
	n/a	n/a		
Openair Plasma Nylon Lord 320/322 Foam	46.65	240.38	275.31	36.46
	50.81	261.83		
	59.78	309.91		
	62.60	323.21		
	54.84	282.51		
	45.48	234.05		
Acid Wash Nylon Lord 320/322 Balsa	75.09	388.98	384.77	24.89
	77.84	402.84		
	n/a	n/a		
	80.36	413.39		
	69.04	356.33		
	69.73	362.30		
Acid Wash Nylon Lord 320/322 Foam	51.57	266.09	281.85	44.83
	71.09	366.93		
	51.33	264.24		
	51.58	265.85		
	46.35	237.95		
	56.72	290.07		

Table 13-2: Dynamic polypropylene edgewise compression strengths

Sandwich Configuration	Max Load (kN)	Ult. Strength (MPa)	Average Ult. Strength (MPa)	Std. Deviation (MPa)
Openair Plasma Polypro Dow Lesa w/ Primer Foam	32.62	168.36	224.84	57.82
	50.73	262.11		
	33.72	174.11		
	40.01	206.53		
	61.99	320.61		
	41.99	217.30		
Openair Plasma Dow LESA w/ Primer Balsa	37.98	196.36	229.56	27.93
	43.52	224.79		
	40.22	206.99		
	47.90	247.82		
	44.29	227.94		
	53.11	273.48		
Surface Activation Polypro Lord 320/322 Balsa	41.89	214.22	178.79	50.11
	n/a	n/a		
	27.96	143.35		
Surface Activation Polypro Lord 7542 Balsa	21.55	109.62	190.23	114.00
	53.22	270.84		
	n/a	n/a		
Surface Activation Polypro Lord 320/322 Foam	51.48	263.08	246.88	75.42
	31.88	164.68		
	60.92	312.90		
Surface Activation Polypro Lord 7542 Foam	n/a	n/a	159.37	13.79
	33.12	169.13		
	29.28	149.62		

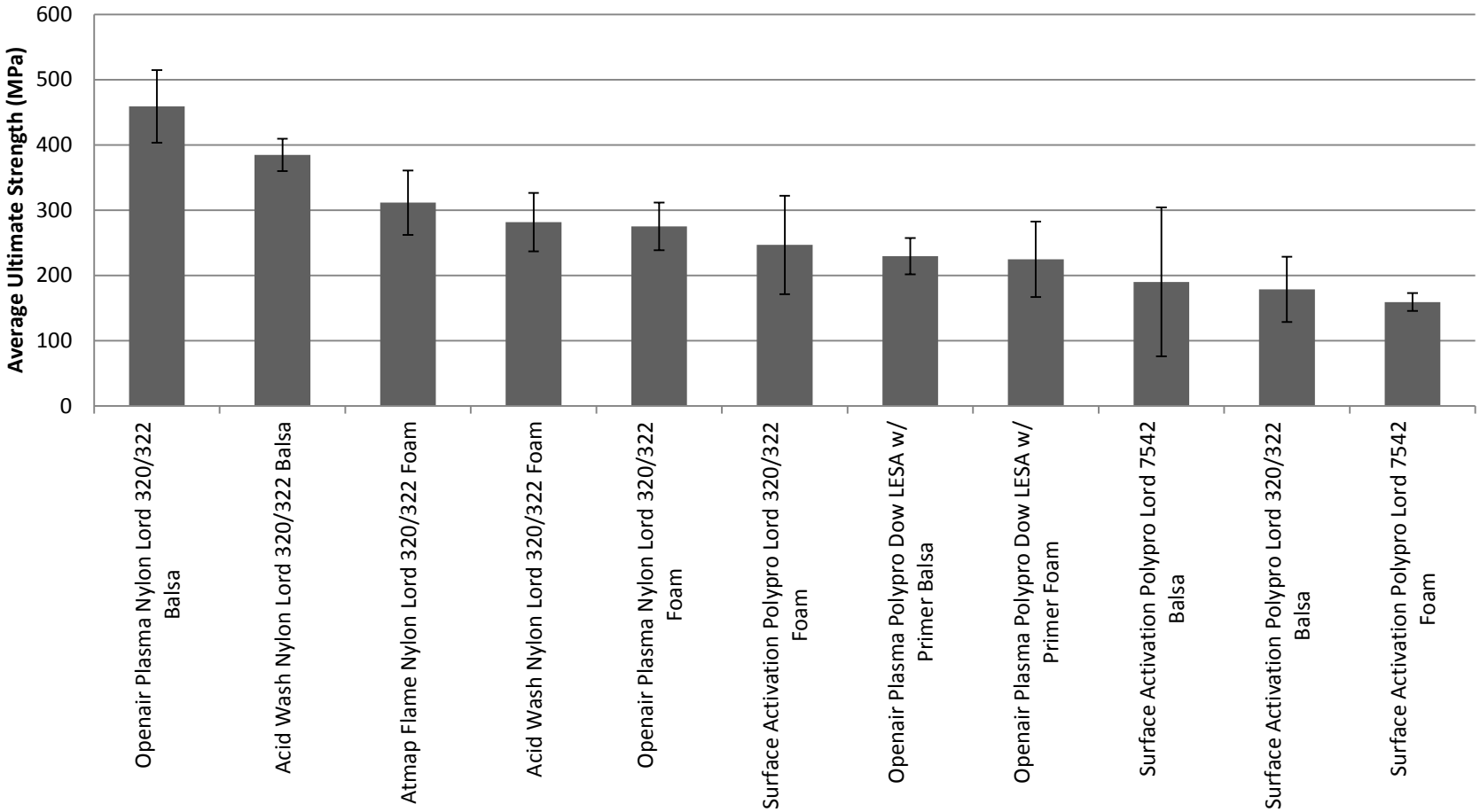

Figure 13-2 : Dynamic edgewise compression strengths

13.4.2 Dynamic Energy Absorption

The dynamic energy absorption was computed and summarized in Tables 13-3 and 13-4 and can be viewed graphically in Figure 13-3. Balsa core sandwich composites had the highest energy absorption of all the sandwich configurations as can be seen in Figure 13-3. The balsa core had higher energy absorption properties than the foam core. The balsa core allowed for a reloading of the sandwich which in turn results in a higher energy absorption. In general polypropylene with foam core absorbed more energy than the nylon with foam core. Results suggest that the polypropylene facesheets allowed for more crushing while still remaining bonded to the foam core.

13.4.3 Dynamic Average Weight-Normalized Edgewise Compression Strength

The average edgewise compression strength was normalized by weight and summarized in Tables 13-5 and 13-6 and can be viewed graphically in Figure 13-4. The average weight normalized edgewise compression strengths showed the difference in the strength-to-weight comparison of the balsa and foam core. Nylon facesheet sandwich composites with the balsa core had the highest normalized dynamic ultimate strength. Nylon facesheet sandwich composites with the balsa core outperformed its foam counterparts greatly as shown in Figure 13-4. Polypropylene facesheet sandwich composites had more mixed results than were shown with nylon facesheet sandwich composites. A polypropylene sandwich composite with the balsa core performed as high as the nylon facesheet sandwich composites with the foam cores as shown in Figure 13-4. However all other polypropylene facesheet candidates produced roughly the same weight normalized average edgewise compression strengths for both the balsa and foam core.

Table 13-3: Dynamic nylon edgewise absorbed energy

Sandwich Configuration	Energy (N m)	Average Energy (N m)	Std. Dev.
Openair Plasma Nylon Lord 320/322 Balsa	417.66	346.22	118.65
	267.78		
	323.29		
	549.84		
	227.27		
	291.47		
Acid Wash Nylon Lord 320/322 Balsa	445.93	521.52	173.04
	453.07		
	n/a		
	405.69		
	475.10		
	827.80		
ATmaP Flame Nylon Lord 320/322 Foam	168.25	185.19	39.17
	157.35		
	n/a		
	229.97		
	n/a		
	n/a		
Openair Plasma Nylon Lord 320/322 Foam	144.57	192.63	46.26
	198.87		
	247.41		
	200.42		
	232.64		
	131.89		
Acid Wash Nylon Lord 320/322 Foam	208.15	206.30	41.80
	191.44		
	206.03		
	176.38		
	170.10		
	285.72		

Table 13-4: Dynamic polypropylene edgewise absorbed energy

Sandwich Configuration	Energy (N m)	Average Energy (N m)	Std. Dev.
Openair Plasma Polypro Dow LESA w/Primer Foam	215.19	237.71	61.37
	141.02		
	228.08		
	305.98		
	302.54		
	233.47		
Openair Plasma Polypro LESA w/Primer Balsa	416.53	555.07	147.36
	824.88		
	557.83		
	582.67		
	511.35		
	437.15		
Surface Activation Polypro Lord 320/322 Foam	236.44	238.28	22.27
	216.98		
	261.41		
Surface Activation Polypro Lord 320/322 Balsa	292.50	280.70	16.69
	n/a		
	268.89		
Surface Activation Polypro Lord 7542 Foam	n/a	178.03	21.17
	163.07		
	193.00		
Surface Activation Polypro Lord 7542 Balsa	284.53	273.53	15.56
	262.53		
	n/a		

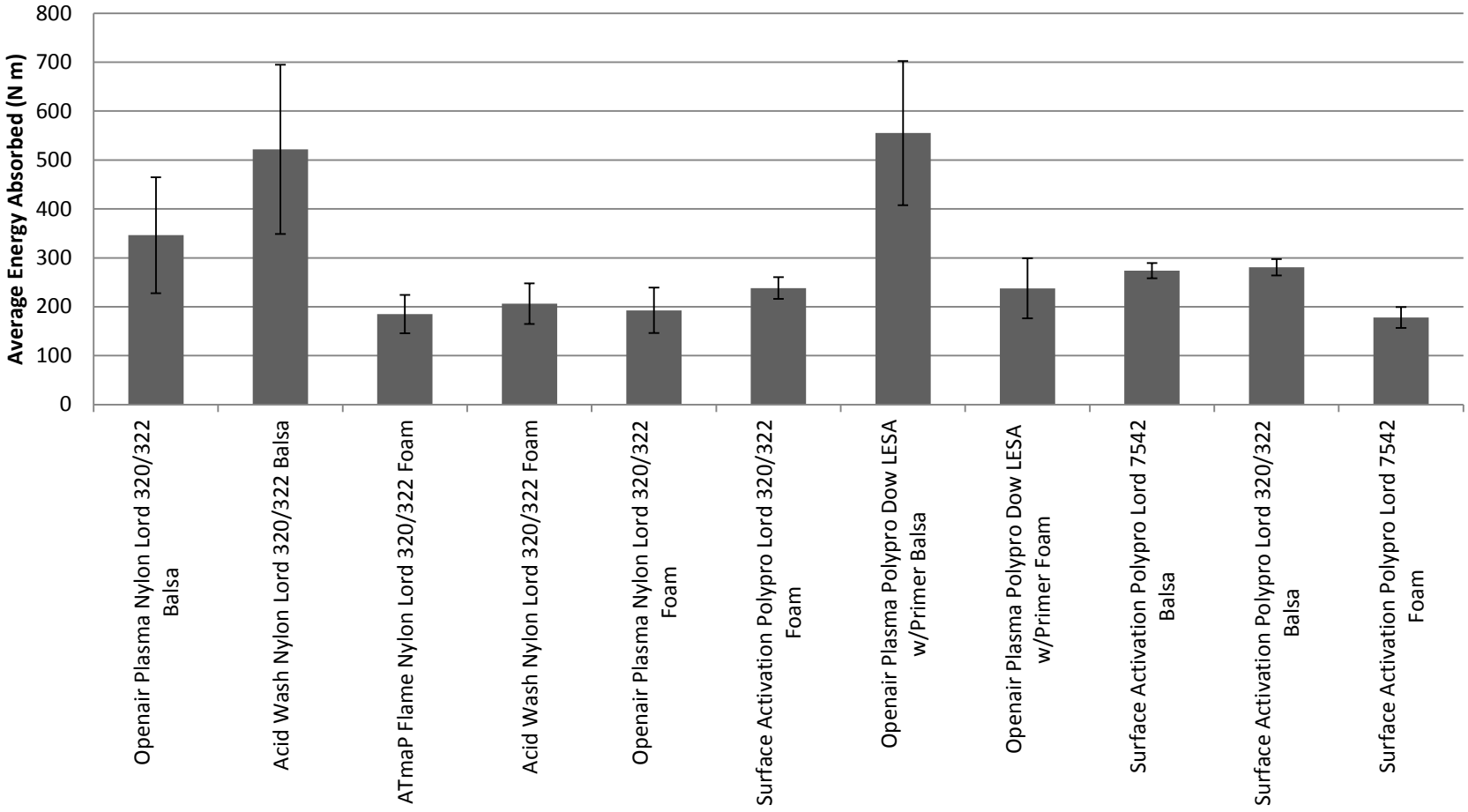

Figure 13-3: Dynamic edgewise compressive absorbed energy

Table 13-5: Dynamic nylon weight-normalized edgewise compression strengths

Combination	Weight (g)	Length (mm)	Width (mm)	Ult Strength per Areal Weight (MPa/kg/m²)	Average Ult Strengh per Areal Weight (MPa/kg/m²)	Std. Dev. (MPa/kg/m²)
Openair Plasma Nylon Lord 320/322 Balsa	74.35	127.00	76.61	55.93	60.28	6.61
	74.95	127.15	76.53	67.61		
	74.47	127.03	76.56	64.97		
	74.24	127.15	76.58	66.03		
	70.10	127.03	76.89	53.12		
	76.46	127.03	76.68	54.02		
Atmap Flame Nylon Lord 320/322 Foam	79.91	127.20	76.28	42.28	37.99	5.98
	79.62	126.97	76.48	31.16		
	78.79	126.90	76.43	n/a		
	79.13	126.90	76.38	40.53		
	78.65	127.08	76.71	n/a		
	75.54	127.15	76.43	n/a		
Openair Plasma Nylon Lord 320/322 Foam	77.40	126.95	76.40	30.12	33.67	3.98
	78.90	126.92	76.40	32.18		
	79.62	127.18	75.95	37.60		
	80.97	127.15	76.25	38.70		
	79.41	127.08	76.43	34.55		
	78.79	127.03	76.50	28.87		
Acid Wash Nylon Lord 320/322 Balsa	72.60	127.79	76.00	52.03	51.01	3.59
	73.64	127.05	76.07	52.87		
	71.81	128.14	76.12	n/a		
	72.72	127.46	76.53	55.45		
	72.07	127.05	76.28	47.91		
	73.83	125.88	75.77	46.80		
Acid Wash Nylon Lord 320/322 Foam	79.94	126.59	76.30	32.15	34.05	5.49
	79.87	126.52	76.28	44.33		
	80.11	126.64	76.48	31.95		
	80.51	126.42	76.38	31.88		
	80.90	126.52	76.68	28.53		
	79.74	126.70	76.99	35.48		

Table 13-6: Dynamic polypropylene weight-normalized edgewise compression strengths

Sandwich Configuration	Weight (g)	Length (mm)	Width (mm)	Ult Strength per Areal Weight (MPa/kg/m²)	Average Ult Strengh per Areal Weight (MPa/kg/m²)	Std. Dev. (MPa/kg/m²)
Openair Plasma Polypro Dow Lesa w/ Primer Foam	79.44	126.85	76.28	20.51	25.82	6.14
	84.19	126.72	76.20	30.06		
	85.93	126.85	76.25	19.60		
	82.58	126.39	76.28	24.11		
	86.45	126.80	76.12	35.80		
	84.48	127.00	76.07	24.85		
Openair Plasma Dow LESA w/ Primer Balsa	61.97	126.42	76.15	30.50	35.39	3.81
	59.50	126.09	76.23	36.31		
	61.78	127.30	76.50	32.63		
	66.21	128.09	76.10	36.49		
	63.70	127.13	76.50	34.80		
	63.73	126.80	76.45	41.60		
Surface Activation Polypro Lord 320/322 Balsa	77.03	126.52	76.99	27.09	22.29	6.79
	76.08	126.70	77.04	n/a		
	79.77	126.77	76.78	17.49		
Surface Activation Polypro Lord 7542 Balsa	77.10	126.92	77.39	13.97	24.09	14.32
	78.25	127.76	77.37	34.21		
	78.67	126.67	76.84	n/a		
Surface Activation Polypro Lord 320/322 Foam	94.63	127.89	77.04	27.39	26.91	8.49
	87.49	126.80	76.23	18.19		
	86.38	126.57	76.66	35.14		
Surface Activation Polypro Lord 7542 Foam	86.96	127.10	76.76	n/a	18.02	2.86
	82.66	127.10	77.09	20.05		
	91.36	126.80	77.04	16.00		

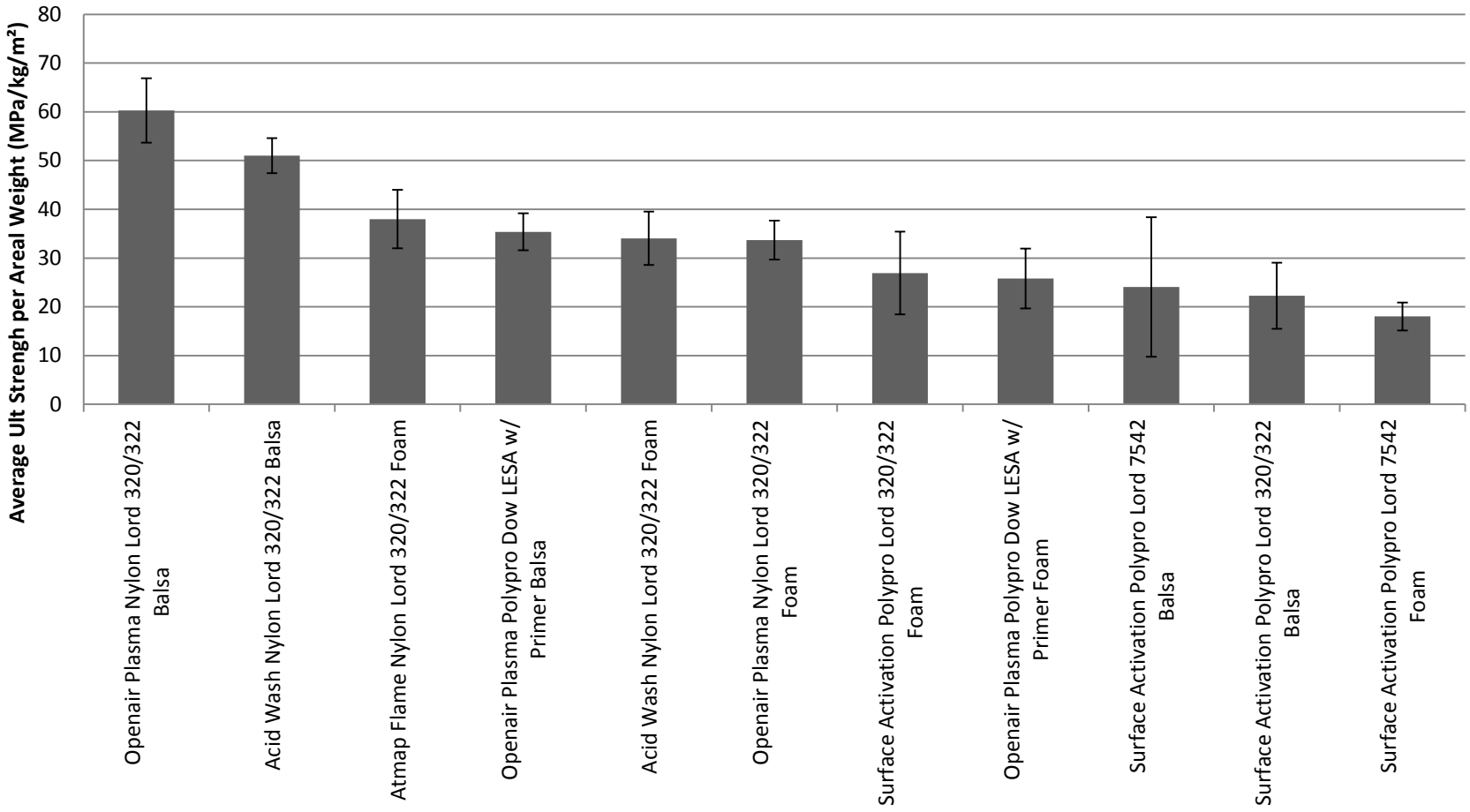

Figure 13-4: Dynamic weight normalized edgewise compression strengths

13.4.4 Dynamic Weight-Normalized Energy Absorption

The dynamic energy absorption was normalized by weight and summarized in Tables 13-7 and 13-8 and can be viewed graphically in Figure 13-5. Sandwich composites made with polypropylene facesheets and balsa cores had the highest weight-normalized energy absorption of all the sandwich configurations tested, followed by nylon facesheet sandwich composites with the balsa core as shown in Figure 13-5. All sandwich configurations with the balsa core, regardless of facesheet type, outperformed their foam core counterparts when normalized by weight. There was a greater variation in the energy absorbed by the balsa core configurations than for the foam core configurations. All the foam core sandwich configurations absorbed roughly the same energy regardless of the facesheet type.

13.5 Summary

The parameter groups that showed the most promise from flatwise and core shear testing were used to produce sandwich panels with two different core materials: balsa and polyurethane foam. These sandwich configurations were tested in dynamic edgewise compression using a test configuration modified from ASTM C 364.

In general, sandwich configurations with nylon facesheets yielded higher dynamic edgewise compression strengths and higher energy absorption than sandwich configuration with polypropylene facesheets. Balsa core sandwich configurations absorbed more energy than foam core configurations. Polypropylene facesheet sandwich configurations with foam cores absorbed more energy than nylon facesheet sandwich configurations with foam cores.

Table 13-7: Dynamic nylon weight-normalized edgewise absorbed energy

Sandwich Configuration	Weight (g)	Length (mm)	Width (mm)	Energy per Areal Weight (N m / kg/m²)	Average Energy per Areal Weight (N m / kg/m²)	Std Dev
Openair Plasma Nylon Lord 320/322 Balsa	74.35	127.00	76.61	54.65	45.42	15.36
	74.95	127.15	76.53	34.76		
	74.47	127.03	76.56	42.22		
	74.24	127.15	76.58	72.12		
	70.10	127.03	76.89	31.66		
	76.46	127.03	76.68	37.13		
Acid Wash Nylon Lord 320/322 Balsa	72.60	127.79	76.00	59.65	68.87	21.54
	73.64	127.05	76.07	59.46		
	71.81	128.14	76.12	n/a		
	72.72	127.46	76.53	54.42		
	72.07	127.05	76.28	63.89		
	73.83	125.88	75.77	106.94		
ATmaP Flame Nylon Lord 320/322 Foam	79.91	127.20	76.28	20.43	22.60	4.86
	79.62	126.97	76.48	19.19		
	78.79	126.90	76.43	n/a		
	79.13	126.90	76.38	28.17		
	78.65	127.08	76.71	n/a		
	75.54	127.15	76.43	n/a		
Openair Plasma Nylon Lord 320/322 Foam	77.40	126.95	76.40	18.12	23.55	5.47
	78.90	126.92	76.40	24.44		
	79.62	127.18	75.95	30.01		
	80.97	127.15	76.25	24.00		
	79.41	127.08	76.43	28.45		
	78.79	127.03	76.50	16.27		
Acid Wash Nylon Lord 320/322 Foam	79.94	126.59	76.30	25.15	24.95	5.26
	79.87	126.52	76.28	23.13		
	80.11	126.64	76.48	24.91		
	80.51	126.42	76.38	21.15		
	80.90	126.52	76.68	20.40		
	79.74	126.70	76.99	34.95		

Table 13-8: Dynamic polypropylene weight-normalized edgewise absorbed energy

Sandwich Configuration	Weight (g)	Length (mm)	Width (mm)	Energy per Areal Weight (N m / kg/m²)	Average Energy per Areal Weight (N m / kg/m²)	Std Dev
Openair Plasma Polypro Dow LESA w/Primer Foam	79.44	126.85	76.28	26.21	27.38	6.94
	84.19	126.72	76.20	16.17		
	85.93	126.85	76.25	25.67		
	82.58	126.39	76.28	35.72		
	86.45	126.80	76.12	33.78		
	84.48	127.00	76.07	26.70		
Openair Plasma Polypro LESA w/Primer Balsa	61.97	126.42	76.15	64.70	86.04	25.03
	59.50	126.09	76.23	133.25		
	61.78	127.30	76.50	87.94		
	66.21	128.09	76.10	85.78		
	63.70	127.13	76.50	78.08		
	63.73	126.80	76.45	66.49		
Surface Activation Polypro Lord 320/322 Foam	94.63	127.89	77.04	24.62	25.98	2.94
	87.49	126.80	76.23	23.97		
	86.38	126.57	76.66	29.36		
Surface Activation Polypro Lord 320/322 Balsa	77.10	126.92	77.39	37.27	35.26	2.83
	78.25	127.76	77.37	n/a		
	78.67	126.67	76.84	33.26		
Surface Activation Polypro Lord 7542 Foam	86.96	127.10	76.76	n/a	19.98	0.92
	82.66	127.10	77.09	19.33		
	91.36	126.80	77.04	20.64		
Surface Activation Polypro Lord 7542 Balsa	77.10	126.92	77.39	36.25	34.71	2.18
	78.25	127.76	77.37	33.16		
	78.67	126.67	76.84	n/a		

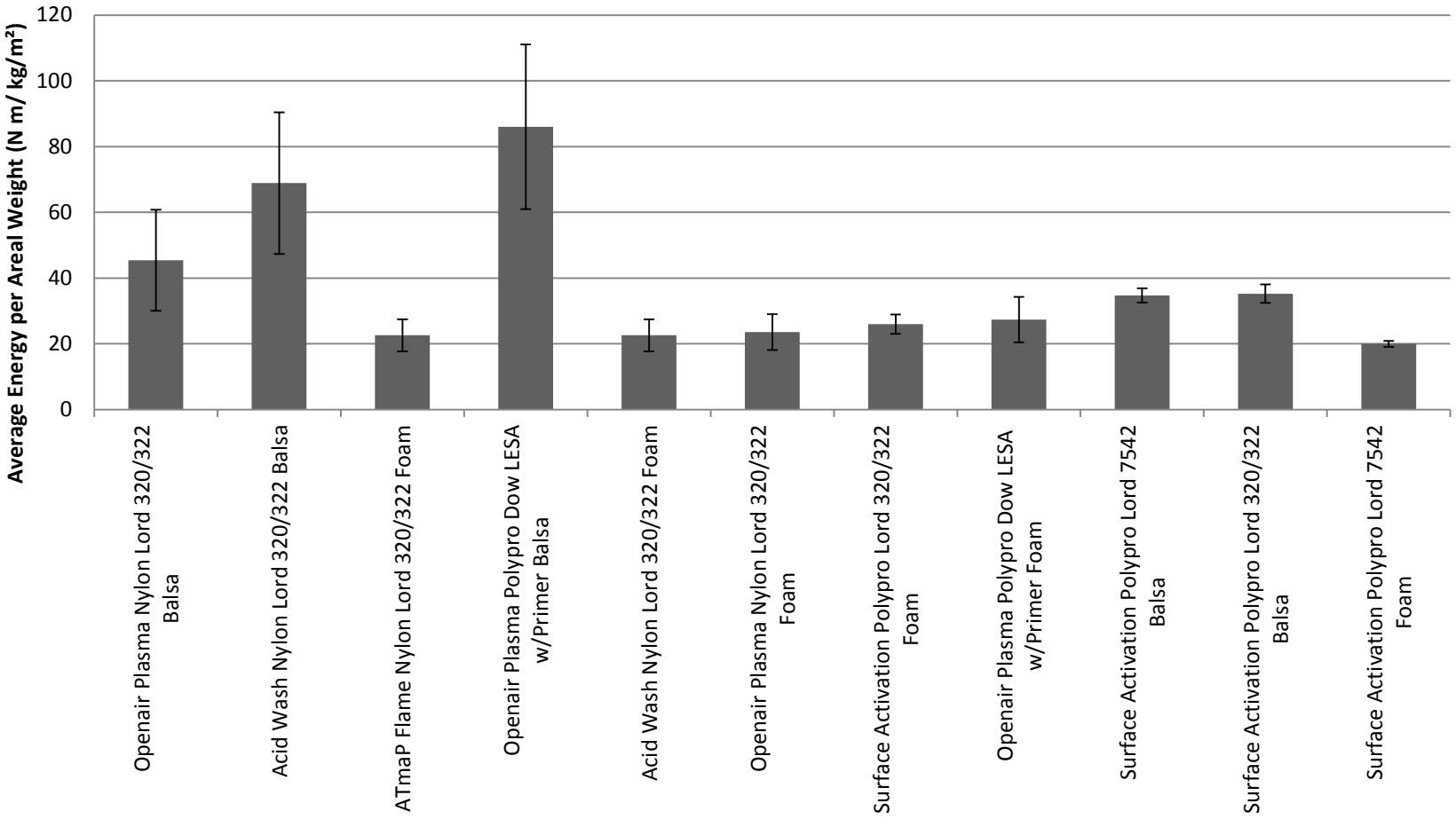

Figure 13-5: Dynamic weight-normalized absorbed energy

14 CONCLUSIONS AND RECOMMENDATIONS

This investigation was a continuation of previous research performed at the University of Utah to establish acceptable adhesion for two groups of thermoplastic composite materials: carbon/nylon and carbon/polypropylene. In lap shear testing, (ASTM D3163), acceptable adhesion was obtained for carbon/nylon by using a zinc stearate mold release with a simple acid wash and two different adhesives: Lord 320/322 and 3M 8239. Adhesion of the carbon/polypropylene was found to be more sensitive to contamination than carbon/nylon.

Kapton film was found to be a suitable mold release for polypropylene/carbon, eliminating the contamination of zinc stearate. Of the four major specialized surface treatments investigated, several different treatment levels were investigated to determine the optimal level for carbon/polypropylene adhesion. A wide range of adhesives were tested at each different treatment level in lap shear (ASTM D3163). An improvement was seen with the development of the Kapton film mold release.

The different parameter groups for carbon/nylon ("nylon") and carbon/polypropylene ("polypropylene") were tested for their adhesion and fracture toughness in cleavage (ASTM D3433). In cleavage, nylon outperformed polypropylene, as was the case in lap shear testing. For nylon, the urethane adhesive 3M 8239 outperformed the toughened epoxy, Lord 320/322. For polypropylene, parameter groups that scored relatively well in lap shear testing also performed well in cleavage testing. The fracture toughness values for polypropylene were nearly half that of the values

obtained for nylon, in agreement with the comparative bond strengths of the two thermoplastic composites.

The most promising candidate from each of the two different thermoplastic categories, acid wash Lord 320/322 for nylon and Openair plasma Dow LESA with Betamate 5404A primer for polypropylene, was selected for additional environmental testing by lap shear (ASTM 3163). Input was sought from the Automotive Composites Consortium (ACC) as to the parameters for the environmental testing. Three environments were investigated: hot, cold, and hot/wet. Acid wash nylon Lord 320/322, showed very little sensitivity to the cold environment, but showed a larger sensitivity to the hot parameters. Openair plasma Dow LESA with Betaprime 5404A primer showed sensitivity to hot and cold environments, with reduced strengths shown in each.

Two of the most promising candidates from each of the two thermoplastic categories were selected to investigate for effect of adhesion on fiber reinforcement testing by lap shear (ASTM 3163). The testing showed a reduced strength in adhesion from the glass reinforcement to carbon in all candidates. The failure mode for the glass reinforcement was fiber/matrix interface failure, where the matrix pulled away from the fibers. Adhesion obtained between the adhesive and the adherend was stronger than the bond between the matrix and the fiber.

Only the most promising candidates from lap shear and cleavage testing were selected for further investigation in the sandwich panel testing. Input was sought from the ACC as to which combinations were most interesting to the industry. Four candidates for nylon and four candidates for polypropylene were selected because of their demonstrated performance and their ability to provide a great number of comparisons.

For sandwich panel testing two different cores were selected: balsa wood and polyurethane foam. The recommended adhesive/surface treatments were applied to the manufacturing of sandwich panels. The sandwich panels were initially tested in flatwise tension (ASTM C 297) and core shear (ASTM C 273). Both of these methods required the bonding of the sandwich to the testing fixture. Due to concerns about surface treatment fade and achieving acceptable adhesion between the adherend and the testing fixture, an alignment fixture was developed to allow for the simultaneous bonding of the adherend to the core and the testing fixture.

In flatwise tension testing, the nylon performed as well as previous carbon/epoxy thermosets with the balsa core, with the exception of the 3M 8239 adhesive, which did not adhere to the balsa core. The nylon did not perform as well as previous thermosets with the polyurethane foam core, even though all the failures were in the core. The polypropylene with the balsa core did not perform as well as the nylon or the previous thermosets, with mostly adhesive failure between the adherend and the adhesive. The polypropylene with the polyurethane foam core had similar strengths to that of nylon with the polyurethane foam, and all failures were in the core.

In core shear testing, both the nylon and polypropylene facesheets with the balsa core performed similarly, but not as well as the previous thermosets. The nylon and polypropylene with the polyurethane foam performed as well as the previous thermosets.

From the initial sandwich panel testing in flatwise tension and core shear, input was sought from the ACC as to which configurations were of particular interest. It was shown that the 3M 8239 adhesive has an incompatibility with the balsa wood and was dropped from testing. Polyurethane foam core was of particular interest due to its

affordability and machineability. An emphasis on the polyurethane foam was taken into the second round of sandwich panel testing.

A method for producing larger sandwich panels from which the individual specimens could be cut from was developed. The sandwich panels were tested in edgewise compression, both statically (modified ASTM C 364) and dynamically using methods previously developed at the University of Utah. The ultimate strength and energy absorption was measured for each method.

For static edgewise compression testing, nylon had a higher ultimate strength than polypropylene independent of the core material. With nylon, the balsa core had a higher ultimate strength than the foam. With polypropylene, the choice of core material had less of an effect: similar adhesive/surface treatment combinations resulted in comparable results with polyurethane foam and balsa wood.

For dynamic edgewise compression testing, nylon had a higher ultimate strength than polypropylene. However, the difference was less significant than that shown by static edgewise testing. All parameters tested showed a higher ultimate edgewise comression strength dynamically than statically, regardless of facesheet or core. For polypropylene, there was more variation between different adhesive/core combinations than was present with the static testing, but the difference was not significant.

For static edgewise energy absorption, sandwich configurations with the balsa core outperformed those with the polyurethane foam core. The highest energy absorption was obtained from nylon/balsa sandwich configurations followed by the polypropylene Sandwich configurations with the balsa core outperformed those with the polyurethane foam core. The balsa core had a more progressive crush which could reload and crush

further. The foam failed and the cracks propagated through the entire specimen, which did not allow for reloading and further energy absorption. The polypropylene with polyurethane foam core outperformed the nylon with polyurethane foam core.

For dynamic edgewise energy absorptions, sandwich configurations with the balsa core outperformed those with the polyurethane foam core, but the difference was generally not as great as was seen in static edgewise compression testing. There was also greater variation in the amount of energy absorbed by balsa core configurations. In dynamic testing, some balsa core configurations greatly outperformed their static energy absorption, while others underperformed their static energy absorption. Nearly all foam core configurations performed equally with very little difference between nylon and polypropylene facesheets.

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